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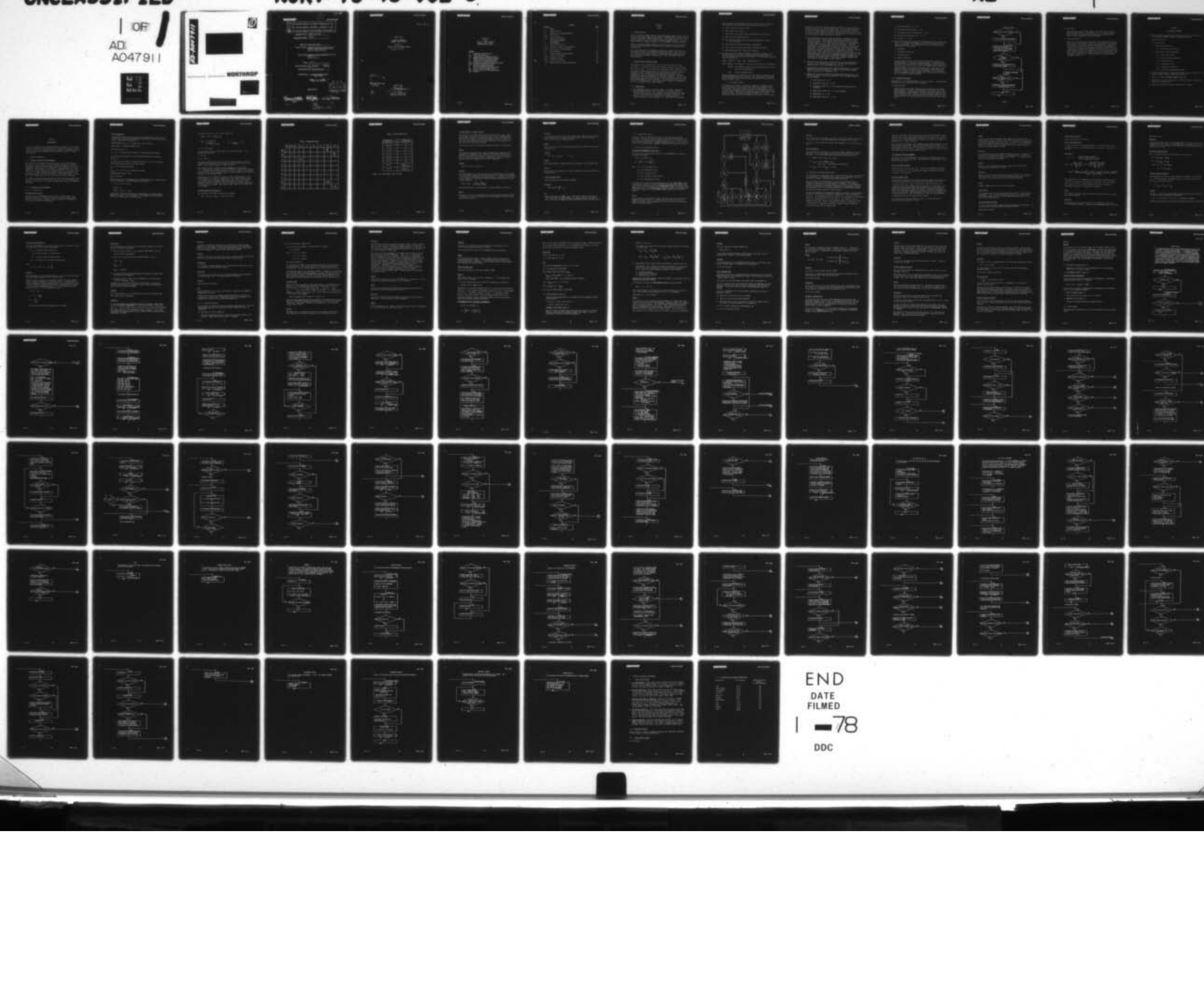

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- [ ] This submittal applies to AN/BRN-7 (Submarine Ω) only.
- [ ] This submittal applies to AN/SRN-( ) (Hydrofoil Ω) only.
- [x] This submittal applies to both AN/BRN-7 and AN/SRN-( ).

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NORTHROP Electronics Division

Copy No. 3

NORT 73-48

AN/BRN-7 COMPUTER
PROGRAM SPECIFICATION

Volume VI

KALMAN FILTER SUBPROGRAM DESIGN

October 12, 1973

Approved by

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Volume VI
of the
AN/BRN-7 OMEGA COMPUTER
PROGRAM SPECIFICATION

Volume

CONTENTS

SECTION 1

SCOPE

1.1 IDENTIFICATION

Volume I, Submarine OMEGA Computer Program Performance Specification, defines the functional requirements for the Submarine OMEGA Computer Program which is used by the AN/BRN-7 OMEGA Navigation Set. The Navigation set and the OMEGA program together comprise the Submarine OMEGA Navigation System. The tape which defines the computer program is entitled AN/BRN-7 Navigation Program

Volume II, Submarine OMEGA Computer Program Design Specification, allocates the functional requirements of Volume I to the computer routine and sub-program level.

This volume describes the subprogram designated as Kalman Filter which has the abbreviation CF in the program listing (Volume XIII). Note that in all the thirteen volumes which comprise the Submarine Omega Computer Program Specification the designators Combinational Filter and Kalman Filter are interchangeable.

1.2 KALMAN FILTER SUBPROGRAM TASKS

The outputs of the tracking filters are well-filtered values of phase-difference, φ, along with the estimates of phase variance, $\sigma^2_{\varphi\varphi}$, and phase rate variance $\sigma^2_{\dot{\varphi}\dot{\varphi}}$. It is within the combinational filter operations that the outputs of the tracking filters are statistically, optimally combined, arriving at "best" estimates of system position and velocity. The combinational filter also performs the coordinate conversion from phase difference to geodetic coordinates (latitude and longitude). The rate of change of frequency between the local oscillator in the receiver and transmitted OMEGA signals is also determined. The combinational filter is also used for lane determination. Lane determination (laning) is accomplished by use of a multiple state vector technique.

1.2.1 Introduction

a) The combination filter is a Kalman filter. The Kalman approach to filtering and prediction can be described as a linear, recursive, minimum variance filter. The fundamental concepts involved are those of state, state transition, measurement, and optimal weighting. The states of the filter are differentials of system parameters; i.e., error in position, error in velocity, etc. The states of the system

are described by the solution of linear vector difference equations. The equations upon which filter operations are predicated are:

1) $X(K) = \varphi (K, K-1) X (K-1) + V(K)$

2) $Y(K) = M(K) X (K) + U(K)$

where X(K) is the vector state of the system error (Table 1)

3) $\varphi(K, K-1)$ The transition matrix.

4) V(K) system forcing function (for Kalman operations a white noise sequence)

5) Y(K) A vector of state observables (measurement)

6) M(K) A state transformation matrices (Extraction matrix)

7) U(K) Measurement noise (white noise sequence)

b) The Kalman technique linearly combines the previous estimate X with the measurement to arrive at a minimum variance estimate which is then time updated until the next measurement. The measurement operation is best described by:

$$\hat{X}(K/K) = \hat{X}(K/K-1) + b(K) \; [Y(K) - M(K) \hat{X} (K/K-1)]$$

where: $\hat{X}(K/K)$ new estimate of state at time K based on K measurements

$\hat{X}(K/K-1)$ Time updated prediction of previous estimate at time K based on K-1 measurements

b(K) optimal weighting vector

Optimal weighting is determined by means of recursive techniques based upon obtaining minimum error variances. This weighting is a function of the covariance of the difference between system error state and estimation of state; i.e.:

$$P = E \; [(X-\hat{X}) \; (X-\hat{X})^T]$$

The combinational filter is, therefore, capable of computing optimal estimates of position and velocity along with other elements of its state vector. The filter utilizes two types of observations. One is the difference between the phase difference of the tracking filter and a value of phase difference based upon the combinational filter's time-updated position. The other observation consists of a received correction to position entered through the C & I Panel. Based on these

measurements, the filter computes optimal estimates of: position errors, driving velocity errors, and oscillator drift. The recursive formulation of filter operations permits each measurement to be processed and then discarded. In this fashion the values of previous measurements do not have to be stored in the computer, since all the information is contained within the state estimate vector and covariance matrix.

c) The uncertainty in position error can produce an ambiguity in lane count, the number of wave lengths between the transmitting station and the receiver. This ambiguity exists primarily when the system is first turned on. To resolve this lane ambiguity, a multiplicity of state vector estimates X_ℓ is carried by the filter. These X_ℓ correspond to the several possible lanes or integral values of phase measurement. As measurements corresponding to the three different frequencies are taken the ambiguity in lane count is reduced. Measurements from different stations tend to further reduce the lane uncertainty. The overall effect is a reduction in the number of state vector estimates X_ℓ that can be considered reasonable estimates of the true state vector until only one reasonable estimate remains. The criterion for reasonableness is based upon variance considerations. An average of the X_ℓ, X_{AVG}, is also computed.

d) The error vector has a rank of nine to allow for the possible error sources in various OMEGA mechanizations. In the phase difference approach five of the nine elements are utilized.

e) The estimates described above are treated computationally in the combinational filter as elements of a vector (= error state estimate vector = state vector = estimator = X).

f) Before the intra-cycle operations are described mathematically, the vectors and matrices which are required to carry out these operations will be defined.

1) State vector (X: 9 x 1)

2) Transition matrix (Φ: 9 x 9)

3) Covariance matrix (P: 9 x 9, symetric and positive semi-definite)

4) System Noise Matrix (R: 9 x 9 and diagonal)

5) Measurement (Y: 1 x 1)

6) Measurement Matrix (M: 1 x 9)

7) Measurement Noise (C: 1 x 1)

8) Measurement-residual (Res: 1 x 1)

9) Measurement-residual variance (V: 1 x 1)

10) Optimum weighting vector (b: 9 x 1)

11) Epsilon (ϵ : 1 x 1)

g) Interfacing requirements with other subprograms have been touched upon above. A restatement and summary will aid in clarification of the operations performed. The subprograms that will interface with the combinational filter include:

1) Navigation

2) Propagation Prediction

3) Tracking Filters

4) Control & Indicator

The interfacing with the first routine includes mode corrections to system position, and corrected system velocities. Interfacing with the last routine, in addition to display functions, includes position correction measurement residual data. The tracking filter supplies ϕ, $\sigma^2_{\phi\phi}$ and $\sigma^2_{\dot{\phi}\dot{\phi}}$ for a particular station/frequency. Knowledge of combinational filter utilizations and resetting of tracker filter parameters is required for this particular interface. The interfacing with the propagation routine includes the C element and $\dot{\phi}$ corrections for the particular station/frequency.

1.2.2 Kalman Task Summary

The overview of the Kalman Subprogram is given in Figure 1. The following represent the tasks performed by the subprogram.

a) Initialization

Initialization occurs after synchronization and whenever the initial time or position is entered by the operator if the entry occurs after synchronization. Initialization consists of setting the Process, NO KICK, and Kalman Started markers; setting the Station Check and state vector counters to zero, and inializing the covariance matrix (P), the transition matrix (Φ), the noise matrix (R) and the first state vector (X).

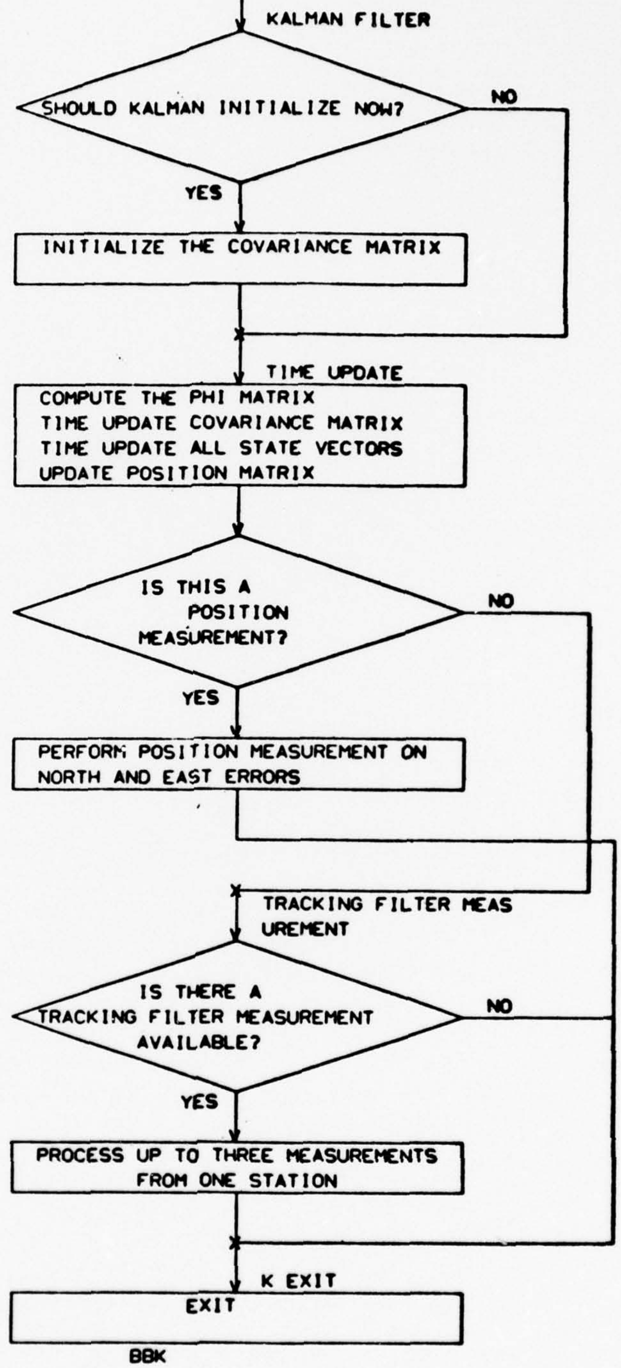

KALMAN FILTER
SHOULD KALMAN INITIALIZE NOW?
NO
YES
INITIALIZE THE COVARIANCE MATRIX
TIME UPDATE
COMPUTE THE PHI MATRIX
TIME UPDATE COVARIANCE MATRIX
TIME UPDATE ALL STATE VECTORS
UPDATE POSITION MATRIX
IS THIS A POSITION MEASUREMENT?
NO
YES
PERFORM POSITION MEASUREMENT ON NORTH AND EAST ERRORS
TRACKING FILTER MEAS UREMENT
IS THERE A TRACKING FILTER MEASUREMENT AVAILABLE?
NO
YES
PROCESS UP TO THREE MEASUREMENTS FROM ONE STATION
K EXIT
EXIT
BBK

FIGURE 1

b) Time Update

The operations consist of time update of the state vector (X) and covariance (P) matrices. This requires the use of the transition matrix Φ which will mathematically propagate the expected errors across the time interval since the last update.

c) Measurement Update

There are two measurement types available and, therefore, generated prior to measurement update. They are: 1) Tracking filter estimate of the phase of a station/frequency combination, and 2) Navigator inserted position correction. For the first type, the measurement is utilized for estimation of the entire system error model while the second type is utilized for resetting of position error in accordance with navigator indication of quality fix. For each measurement type however, the operations are similar and consist of generation of the measurement residual, Res_i, extraction matrix, M_i and measurement confidence scalar, C_i.

SECTION 2

APPLICABLE DOCUMENTS

a) Submarine OMEGA Computer Program Performance Specification (Volume 1 of the Submarine OMEGA Computer Program Specification)

Applicable Sections

3.1 Introduction

3.2 Functional Description

3.2.5 Detailed System Operations

3.3 Detailed Functional Requirements

3.3.2 Signal Input Timing

3.3.9 Phase Difference Processing

3.3.10 Tracking Filters

3.3.11 Combination Filter

3.3.12 Propagation Prediction

3.3.13 Velocity and Heading Processing

b) Submarine OMEGA Computer Program Design Specification (Volume II of the Submarine OMEGA Computer Program Specification).

c) NORT 71-41, NDC 1070 MACRO ASSEMBLER, MAY 1971

d) NORT 68-115A, Detailed Description of NDC-1070 Computer Instructions, Revision A, February 1970.

e) NORT 69-87A, NDC-1070 Flow Chart Program, User's Manual.

SECTION 3

REQUIREMENTS

In order to understand the program description contained in the following pages, it is necessary that the reader will have become familiar with the associated functional requirements found in Volume I, Performance Specification, and with the subprogram allocation found in Volume II, Design Specification.

3.1 DETAILED DESCRIPTION

3.1.1 Reference Labels to Flow Diagrams

The code used to reference the particular block in the flow diagrams, Section 3.2, is as follows: The first number, preceded by a p, is the page number found in the upper right corner of the diagrams. This will be followed by a slash sign (/) to separate the page number from the block designator. The designator will either be a mnemonic label (e.g., TEST SYNC), a local label indicated by a dollar sign ($), or an integer. The two types of labels reference the particular information block, on the given page, to which the label is attached. The integer number, n, means that the referenced block is the n^{th} block from the top of the page.

For instance, p8/3 would refer to page 8 and the third information designation down; The label p1/$2+3 refers to page 1, and the 3^{rd} information block after the label $2; p2/7,8,9 refers to page 2 and the 7^{th}, 8^{th} and 9^{th} blocks.

3.1.2 Description of Flow Diagram

3.1.2.1 Initialization

P1/Kalman Filter to p2/1

The next Ω-task is END BURST and will occur in 5 milliseconds. The Combinational Filter is entered 5 milliseconds prior to the End Burst marker on every station. However, only at a station A transmission on 10.2 kHz will the filter be sequenced.

P2/2 through P3/3

Initialization occurs after synchronization and whenever the initial time or position is entered by the operator if the entry occurs after synchronization. Initialization consists of:

STATE VECTOR Counter, N = 0 (represents 1 state vector)

State vector: Initialize number 1 to 0.

Covariance matrix = 0.

$P_{11} = P_{22}$ = inserted position quality if position has been entered.

P_{11} and P_{22} are set equal to the values existing when the system was turned off.

P_{11} and P_{22} are set equal to a position quality of (0 n mi) if time has been entered and position has not been entered.

P_{44} = (0.25 microsec/microsec)^2.

σ^2_{kick} = (5 n mi)^2 or P_{11}, whichever is largest.

Kalman Started marker = true

R_{ij} matrix saved

When the PHI matrix is separated into a modified PHI plus an identity matrix then the elements of the modified PHI are as follows:

$$\varphi(1,8) = \varphi(2,9) = \Delta t/R_o$$

$$\phi(3,4) = \Delta t$$

$$\phi(8,8) = \phi(9,9) = -\beta_v \Delta t$$

This concept is further described in the description of the PHI P PHIT subroutine on page 27 of flow diagram. The elements of modified PHI are stored in 14 words, some of which are zero.

The system noise matrix, R, is zero, except for

$$R(8,8) = R(9,9) = 2\sigma^2_{NAV}\, \beta_v \Delta t.$$

σ_{NAV} = 3 ships log
10 manual
20 NO RATE Aiding

$$\beta_v = \frac{1}{.05(3600)} \quad sec^{-1}$$

3.1.2.2 Time Update

The operations consist of time update of the X and P matrices. The equations utilized are:

1) $\hat{X} = \Phi\hat{X}$

2) $P = \Phi P \Phi^T + R$

Both these equations require the use of the transition matrix Φ which mathematically propagates errors across the time interval since the last update. The transition matrix is shown in Table 1.

The transition matrix provides only the propagation of predictable (i.e., deterministic) elements of X and P across the computational interval Δt_u. Propagation of the random effects across this interval is accomplished by means of the additive diagonal matrix R. Table 2 specifies the diagonal elements of R by navigation mode.

Investigation of the elements in Φ and R reveals the dependence of time between updates as a factor in computation. This update should be done at a constant rate to minimize computational cost. Due to the dynamical errors associated with maneuver and the utilization of velocity error elements as output information, it is felt that this iteration time should be a maximum of 30 seconds. The iteration time chosen is the natural one of 10 seconds.

<u>P3/TIME UPDATE (P) through P4/3</u>

The subroutine PHI P PHIT is used twice to compute

$$P(K) = \Phi(K, K-1)\; P(K-1)\; \Phi\,(K, K-1)^T + R(K)$$

TABLE 1 TRANSITION MATRIX

	$-\delta\theta_3$	$\delta\theta_2$	t_o	$\dot{t}_o$	P_1	P_2	P_3	δV_2	δV_3
$-\delta\theta_3$	1							$\frac{\Delta t}{R_o}$	
$\delta\theta_2$		1							$\frac{\Delta t}{R_o}$
t_o			1	Δt					
$\dot{t}_o$				1					
P_1					0				
P_2						0			
P_3							t		
δV_2								$1-\beta_V\Delta t$	
δV_3									$1-\beta_V\Delta t$

TABLE 2 SYSTEM NOISE MATRIX

ELEMENT NO.	EXPRESSION
(1, 1)	0
(2, 2)	0
(3, 3)	0
(4, 4)	0
(5, 5)	0
(6, 6)	0
(7, 7)	0
(8, 8)	$2\sigma^2_{NAV}\beta_V \; \Delta t$
(9, 9)	$2\sigma^2_{NAV}\beta_V \; \Delta t$

NOTE: All off-diagonal terms are zero.

P4/TIME UPDATE X to page 4 bottom

During most of the cruise there will be only one state vector. However, under adverse conditions, the variances increase and the OMEGA system becomes uncertain about the position estimate. Under these conditions there will be a number of state vectors generated, each of which may be the vector representing the true position and must be maintained until that time that the variances decrease.

In the entry block of the loop the average state vector is initialized.

P4/$6,

The variable XX represents one of the 9-element state vectors which is assembled from component parts. Becase the last five elements of the multiple state vectors are identical only the first four are saved for each of the multiple state vectors. Consequently, when each is time updated it must be assembled with the last 5 components.

P4/$6+2

$$\hat{X}_k\,(K) = \Phi(K, K-1)\;\hat{X}_k\,(K-1)$$

P4/$6+4

The combinational filter generates new state vectors based upon the values of the residuals computed for a given tracking filter output (corresponding to a given station difference and frequency pair). An average state vector is also computed by computing an element-by-element average over the state vectors generated:

$$\hat{X}_{avg} = \hat{X}_{avg} + \frac{\hat{X}_k - \hat{X}_{avg}}{\#\text{ of state vectors}}$$

The average variance is also computed. See p33, AVERAGE X subroutine.

P5/1,2

The scatter vector is a 9-element matrix, each element of which represents the variance of the error estimates of the same respective element of the multiple state vectors.

P5/2,3,4

If the position scatter error is less than 4.76 n miles then the position error elements of the average state vector XXX(1), XXX(2) are used to correct the position via the R_{ij} matrix.

P5/$7

Each state vector is now corrected by deleting the correction just made to the R_{ij} matrix.

P5/$7+3

$$\Delta V_i = \Delta V_i - \beta_v \Delta V_i \Delta T \qquad i = 1,2$$

P6/1-8

This page manages the updating of ΔV_i with respect to the NAV Mode used.

P7/1,2

The system is confirmed when all three frequencies from three stations are being received.

P7/$52 through P7/$53

Routine maintenance of covariance diagonal.

P7/$53+1

$$\text{Time increase} = \int_0^t \dot{t}_o \, dt$$

P8

Routine Maintenance of OMEGA clock. When above integral accumulates to 5 msec. then one interrupt is added to or subtracted from the computer time. See Volume IV, OMEGA Processing Subprogram Design, END SLOT routine.

3.1.2.3 Measurement Update

As stated in the task description there are two types of measurement available; Position Fix from the operator, and a Tracking Filter measurement. Each is processed with a different assumption; with a position fix the computer program assumes the OMEGA operator is correct, with a tracking filter fix the software will attempt to compromise and resolve differences.

a) Position Fix Measurement Update

P9/POSITION MEASUREMENT through P10/2

After setting up arguments for position fix the COMPUTE BI & C subroutine is entered to compute

$$Q_i(K) = M_i\ P(K)M_i^T + C_i$$

$$b_i = \left[PM_i^T + M_i^T\ \epsilon\right]\left[Q^{-1}\right]$$

where b_i is the weighting vector

M_i is the Measurement matrix

P is the covariance matrix

ϵ is the divergence control factor

C_i is the measurement variance.

Following the calculations for the weighting vector the MEASUREMENT UPDATE X subroutine is called. To fully understand the measurement updating process, refer to the description of the MEASUREMENT UPDATE X subroutine, flow diagram page 36. It is possible that a state vector has not been generated. The overall sequence of the MEASUREMENT UPDATE X subroutine is shown in Figure 2.

P10/4

The measurement is unsuccessful due to either the first (N) or second (E) component of position error. In either case the Flag B is set true to bypass the 36-mile limit on position error, which is part of the new state vector acceptability check.

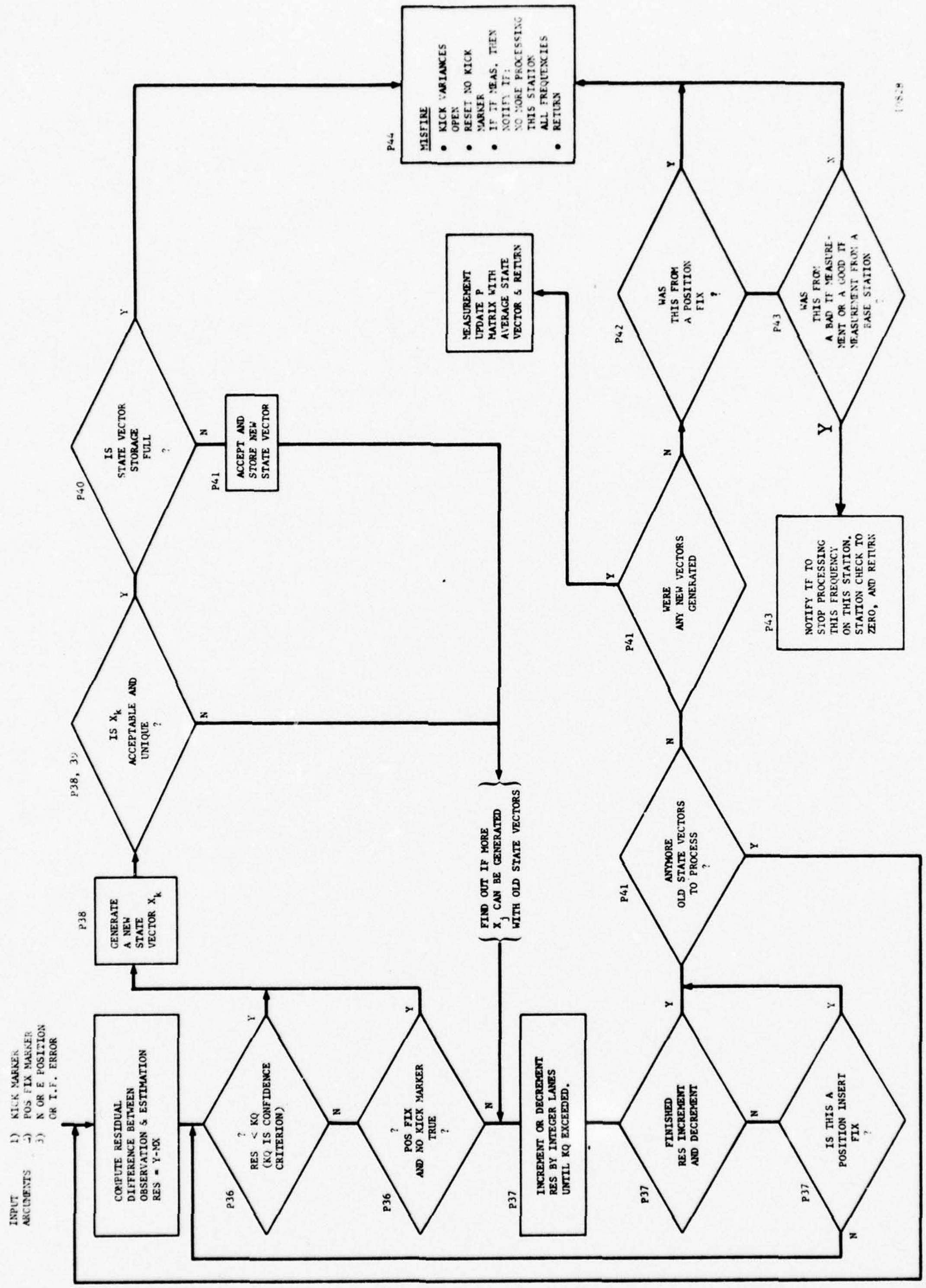


FIGURE 2 MEASUREMENT UPDATE X SUBROUTINE

P10/5,6

If the unsuccessful measurement was due to the second component of position error then return to the measurement update subroutine and try again.

If due to a first component (N) then reset arguments for the second and try again.

P10/7 through P11

The measurement was successful. If there is another component to process then return to the measurement update subroutine and process the second component. If not then establish sigma KICK by performing in order:

1) $S(MAX) = \text{max of } (P_{11}, P_{22}, \sigma_{KICK})$

2) $\sigma_{KICK} = \text{min of } (S(MAX), C_{pos})$
   where C_{pos} is the position variance used.

3) $\sigma_{KICK} = \text{max of } (\sigma_{KICK}, 5 \text{ n miles})$.

b) Tracking Filter Measurement Update

The tracking filter measurements occur at an asynchronous rate. Availability of a measurement is indicated by the n counter of the tracking filter, as described in Volume V, Tracking Filter Subprogram Design.

When a tracking filter measurement for some phase-difference pair is accepted, an estimate of that measurement is computed. This computed estimate is based upon the present position as indicated by the Navigation Routine and propagation corrections determined by the Propagation Routine. The measurement Y_i is the difference between this computed phase estimate and the phase estimate from the tracking filter.

For each measurement, the measurement residual is computed. The measurement residual is the difference between the measurement Y_i and its predicted value M_iX. The measurement matrix M_i consists of the algebraic relationships between the measurement and the error state X. The elements of M_i are computed within this routine. The remaining parameter, measurement noise, is an addition of $\sigma^2_{\phi\phi}$ and the confidence figure from the propagation routine associated with its computations.

After the time-update of the state vector and the covariance matrix, the tracking filter outputs are scanned station-pair by station-pair, starting with the station-pair immediately following the last used by the combinational filter. As mentioned above a tracking filter output is ready to be processed by the counter criterion.

When a station is processed, all frequencies meeting the readiness criteria are processed sequentially. When a tracking filter has been read, the combinational filter resets the tracking filter variances to their velocity-mode-dependent initial values. If no tracking filters are ready for use by the combinational filter, the routine exits.

P12/TRACKING FILTER MEASUREMENT

The search for a good measurement to process in the combinational filter begins with the station used last. The Difference Frequency Marker is set and may be reset later.

P12/$13 through P13/$63+2

Checks the size of P_{11} and $P_{11} + P_{22}$. This is a programming convenience in the case that $P_{11} + P_{22}$ overflows the register resulting in a small remainder in the register.

P13/$12 through P13/$1

An additional constraint on the station selection scheme exists when the variance on position error as carried in the covariance matrix exceed 4 n miles squared $[P_{11} + P_{22} > (4 \text{ n miles})^2]$. When this occurs, two frequencies from a given station must be available for processing. This constraint holds down the number of extraneous state vectors generated when a large uncertainty in position exists. A measurement generated under these conditions consists of the difference of the measurements (Y_i) of the two frequencies. The measurement matrix (M) also is computed by differencing the M_i for the two frequencies. Thus only one measurement is generated from the two tracking filter outputs.

The frequency-need counter, P13/$1, is set to 2 if the difference frequency mode is used, and 1 if not.

P13/$3

If the station under scrutiny has been disabled by the operator the sequencing will branch to P14/$2. The check on the number of frequencies will return sequencing to this same test, i.e., P13/$3. The third time through this loop will find the program at P14/$2 + 1 where a NO branch results in P14/$28, ending the check on this station and returning to P12/$13 for another station to check.

P14/1,2,3

If the station has not been disabled then the N counter is checked. If $N \geq 3$ then the frequency-need counter is decremented by 1. See P13/$12 description for setting the frequency-need counter. The frequency-need counter is permitted to go negative.

P14/$2

Until all three frequencies have been checked for this station the sequencing will branch back to P13/$3.

P14/$2+1

After all three frequencies have been checked there must be at least one usable frequency, or two if in the difference frequency mode. If so, continue; if not, then the station is not usable (P15/$28).

P14/6

Submarine OMEGA does not use rho-rho so continue.

P14/7, P15/1

If the measurement is not from the base station then it is an available measurement. If it is from the base station then to be classified as an available measurement the last available measurement must not have been from the base station.

P15/$28 through P15/$28+2

If all stations have been checked then no measurements are processed. If not then return to P12/$13 and select another station.

Measurement Available

P15/$4 through P16/$71

Setup for measurement processing.

P16/$7 through P16/$7+5

If $\sigma^2_{\phi\phi} \geq .031$ then the corresponding data is not classified as a good measurement and the corresponding marker is set false; otherwise it is set true.

P17/$42+4,5

$$r_{11} = r_{11} \frac{(\text{earth's polar radius})^2}{(\text{earth's equatorial radius})^2}$$

$$\theta_1 = \tan^{-1} \frac{\left|\vec{R}_1 \times \vec{S}\right|}{\vec{R}_1 \cdot \vec{S}} = \tan^{-1} \frac{\sqrt{(\vec{R}_1 \times \vec{S}) \cdot (\vec{R}_1 \times \vec{S})}}{\vec{R}_1 \cdot \vec{S}_1}$$

$$= \tan^{-1} \frac{[(r_{12}s_3 - r_{13}s_2)^2 + (r_{13}s_1 - r_{11}s_3)^2 + (r_{11}s_2 - r_{12}s_1)^2]}{r_{11}s_1 + r_{12}s_2 + r_{13}s_3}$$

The components of the transmitter location vectors (station and base) S must be in geocentric (not geodetic) coordinates. The vector $\vec{R}_1$ is the first row of the R_{ij} Matrix modified by the first equation to change $\vec{R}_1$ from geodetic to geocentric coordinates.

P17/6

This branch insures that base station data and station data will always be processed together.

P17/7,8,9

If station is too close or too far it is not usable due to the lack of interfrequency coherency. Otherwise the measurement loop is initiated.

Measurement Loop

P18/$11+1

After setting Flag D true for a good measurement (or false otherwise) the program checks that there is a measurement on this frequency. All three frequencies will be checked as it is known that a good measurement exists on one or two of them.

P18/$46 through P18/$46+5

This loop computes the first two elements of the M matrix:

$$M1 = M1_{STATION} - M1_{BASE}$$

$$M2 - M2_{STATION} - M2_{BASE}$$

where $M1 = \vec{S} \cdot \vec{R2}\ \lambda/\mathrm{SIN}\ \theta_1$

$$M2 = \vec{S} \cdot \vec{R3}\ \lambda/\mathrm{SIN}\ \theta_1$$

P19/$44 through P19/$49+1

The propagation prediction routine computes an estimate of the variance C_i, of each measurement, designated σ^2_{ppi} for a non-base station and and σ^2_{ppk} for the base station.

$$C_i = \sigma^2_{\phi\phi i} + \sigma^2_{ppi} + \sigma^2_{ppk}$$

P20/1,2

If this is a base station measurement being processed then the M matrix for base-to-base calculations is computed as

$$M_k = [0\ 0\ 0\ 10(j)\ \ 0\ 0\ 0\ 0\ 0]\ ;\ \text{j represents frequency}$$

sequencing continues at P21/$51 where the measurement update is performed.

P20/$50 through P20/$50+5

The subroutine THETAC is used twice to calculate the following for either station-to-base or base-to-base measurements.

Let ϕ_{ci} = predicted phase for station

ϕ_{ck} = predicted phase for base station

$\hat{\phi}_k$ = estimated phase for base-station

$t_i - t_k$ = difference in time between measurements.

then

$$\phi'_{ci} = \phi_{ci} - \phi_{ck} + (t_i - t_k)\ \frac{\hat{\phi}_k}{1°}$$

P21/$51

The measurement, Y, and the epsilon factor, ϵ , are now calculated where $\hat{\phi}_{ik}$ is the measured phase from the tracking filter.

Because of the utilization of fixed point limited word lenth arithmetic for all internal computations, an epsilon factor, ϵ, is specified to prevent divergence of the estimation process. This divergence can result from the buildup of arithmetic round-off and truncation errors leading to loss of positive semidefiniteness of P. An additional use of the epsilon factor is to reduce mismodeling effects.

$$Y_i = \phi_{ik} - \phi'_{ci}$$

$$\epsilon_1 = \epsilon_2 = \frac{C_i}{16\lambda^2}$$

$$\epsilon_3 = \frac{C_i}{16V_\lambda^{\ 2}}$$

where V_λ is the velocity of propagation; a constant.

P21/\$51+2,3

If the combinational filter is in the difference frequency mode then for the first frequency the program

1) Saves M_1, M_2, M_3 and M_4; ϕ_{ik}, C_i' and the KICK LIMIT Q_i (See the Compute BI and C subroutine).

2) Resets this tracking filter by setting n-counter to zero.

$$\sigma^2_{\phi\phi} = \frac{1}{12}$$

$$\sigma^2_{\phi\dot{\phi}} = 0$$

$$\sigma^2_{\ddot{\phi}\ddot{\phi}} = (0.006\pi)^2$$

3) Complements Difference Frequency Marker and updates the Dump counts for this station-frequency.

4) Branches to P18/\$11 where the 2nd frequency will be initiated by calculating $M_{STATION} - M_{base}$.

Eventually this same check will take the "NO" branch to process the second frequency where the variables of item 1) above are differenced with those of the second frequency.

P21/\$90

The weighting matrix, b_i, and the kick limit, Q_i, are calculated using the compute BI and C subroutine.

P21/\$90+1

As indicated beneath this information block and in Figure 2 (under description P9/POSITION MEASUREMENT), if this was considered a good measurement, i.e., $\sigma^2_{\dot{\phi}\dot{\phi}} < (0.00031 \text{ cycle/sec})^2$ and no state vectors were generated, then sequencing exits the Combinational Filter. However, if not a good measurement the sequencing will return to P23/\$10 to see if there are more frequencies to process.

P22/1,23

To continue sequencing at this point a new state vector must have been generated. If more than one state vector was generated, then the Station Check counters are zeroed. If only one state vector, then a bit for this station and frequency is posted in the appropriate location.

P22/$77

Tracking Filters reset as indicated in item 1) under description P21/$51+2,3, unless it is the base station, in which case it is never reset.

P23/$65-$97

The difference frequency marker is set or reset and the Kalman dump counter is incremented for this station-frequency.

P24/1,$92

If there are more frequencies then the program branches to the beginning of the measurement loop. If not then branch to P25/M EXIT.

P24/$91

Discussed under P21/$51+2,3

P25

The NO KICK Marker is set true if the system is confirmed, the KALMAN IN PROCESS Marker is reset.

Preparations are made for Propagation Prediction which is used here as a subroutine to insure that it immediately follows the processing of the Combinational Filter and on the same processing level.

3.1.2.4 Kalman Subroutines

The following are subroutines used by the Kalman Subprogram only. The flow diagram pages upon which the subroutines can be located are given in parenthesis.

a) Initialize P5, P6, P7 (page 26)

   The routine initializes the 5th, 6th and 7th rows and columns of the P matrix. Sigma (P(I) in P26/4 refer to constants.

b) Phi P Phi Transpose (pages 27-30)

This subroutine is designed to multiply PHI by a matrix Z:

$$K = (Z)\ (PHI)^T$$

where Z = X, a 1 x 9 matrix

= P, a 9 x 9 matrix

= P^T, a 9 x 9 matrix

The result replaces Z.

The introductory remarks to the subroutine indicate 14 non-zero elements in the PHI matrix. This is not true and is a leftover from previous modifications. The 14 elements remain, some of which have been zeroed.

The transition matrix is as indicated in Table 1. However, it is multipled as if the unit elements were not present. In other words the phi matrix is separated into the sum of a modified PHI matrix and the identity matrix. After forming the product of P, P^T or X and the modified PHI matrix the subroutine will then concentrate on the product with the identity matrix.

P27/PHI P PHIT

When the Z matrix represents P, then each element of Z is defined by two words, i.e., P is a double precision matrix. The elements of Z=P are stored linearly in the computer as P_{11}, P_{12}, ... P_{19}, P_{21} ... P_{29}, P_{31}, ... P_{99}; each element defined by two words. P is indexed by an increment of 2 with a limit value of 18. These indices are represented by I and J in the flow diagrams.

When Z represents P^T the index I = 18 and J = 2.

When describing mathematically the manipulation of the matrix the fictional index M is used which increments each element of a P row by one as would be expected. The counter K tracks the row number of Z. N tracks the column vector of PHI.

P27/$6

The TEMP vector is a temporary row vector of the product matrix which, when completed, will replace the same row of the multiplier matrix.

P27/$5,$3

The PHI pointer indexes the non-zero elements of PHI. These 14 elements are as indicated in the introductory remarks on page 27. Admittedly some are zero. However, in previous program modifications they were non-zero, and rather than change the program sequencing it was expedient to zero those elements no longer used.

The pointer will index through the 14 elements and use them one by one when indicated by the PHI CODE matrix. This is a 9 x 9 binary matrix which is defined by 9 9-bit registers. A zero bit in a particular register indicates that there is a non-zero element of the modified PHI matrix, in the same relative position as the PHI CODE element, to be multiplied by something. Because of the ordering of these 14 elements the PHI pointer always indicates the proper element to be used as the multiplicand. Succeeding the multiplication the pointer is incremented. Conversely, a one bit in a register indicates a zero element of the modified PHI matrix and no multiplication takes place. This method reduces the number of products in a 9 x 9 matrix from 729 to a more reasonable number. These operations are explained in subsequent steps.

P27/$2

Using M and N the specified bit of PHI CODE Matrix is checked to find out whether the representative element is zero or non-zero.

P28/1

If zero then transfers to P28/$1 where M is indexed and returns to the beginning of the multiplying loops at P27/$2.

P28/2,3,4

If non-zero Z(K,M) multiplies PHI(N,M) and sums with the Nth element of TEMP vector. The PHI Pointer is then incremented.

P28/$1

M is incremented by one. This is done by the index I which is incremented by 2 for a P matrix, 18 for P^T and 1 for X.

P28/$1+1

If M (or I) is within the limits then there are more elements to be multiplied and sequencing returns to P27/$2.

If M exceeds the limit then N is incremented, M is reinitialized.

P28/1

N is tested for limit value. If more columns of PHI to process then sequencing branches to P27/$3. If not then the K'th row operations of Z on modified PHI are completed. It now remains to add in those elements which multiply the identity matrix.

P29/$4 through P30/1

This loop adds Z(K,K) to the K'th element of TEMP.

P30/2,3

TEMP replaces K'th row of Z and K is indexed by 1. If K exceeds limit value (1 or 9) then EXIT.

If not then sequencing returns to P27/$5 for another Z row operation.

c) Compute BI & C (pages 34-35)

Generation of the optimum weighting vector, b_i, requires three expressions. These are: 1) the predicted measurement variance $M_i \, P \, M^T_i$; 2) measurement corruption, or confidence, variance C_i, and 3) the divergence control factor ϵ. The matrix P which is used to generate $M_i P M^T$ for the first measurement residual during a measurement update is that which resulted from the time-update operation on $\hat{X}$ and P.

P34/COMPUTE BI and C through P34/COMPUTE BI

$$Q_i \,(K) = M_i \, P(K) \, M_i^T + C_i$$

$$b_i = \left[PM_i^T + M_i^T \epsilon \right] \left[Q^{-1} \right]$$

The B code is used to indicate to those calculations using b_i whether the first or the second (inverse) was used. It is desirable to maintain $b_i < 1$ so that if the first calculation is >1 then the second is used.

P34/4,5,$6

If $Q < 1/10$ then set $Q = 9/10$

If $Q > 1/10$ then set $Q = 9Q$

P35

If a position measurement then $Q = Q + 2$ n mile

If a tracking filter measurement

then compute upper Kick Limit, KQ_{max}

$$KQ_{MAX} = (\text{KICK LIMIT})^2 + .75\ (\text{cycle}\ )^2$$

where KICK LIMIT = V_λ, the phase velocity (constant)

If $Q < KQ_{MAX}$ set $Q = Q + .04$ cycle

If $Q > KQ_{MAX}$ set $Q = KQ_{MAX}$

Q is now the ACCEPT LIMIT or KICK LIMIT

d) P SYM subroutine (page 31)

Forces the covariance matrix to be symmetric and the diagonal elements to be positive.

If $P(i,i) < 0$ then $P(i,i)$ set to 0

$P(i,j) = P(j,i)$ for $i \neq j$.

ASSEMBLE STATE VECTOR (page 32)

Builds a single 9-element state vector (XX) from one of the 4-element multiple vectors and the 5-element common vector (XXXX). Refer to description of P4/$6 for further description.

e) AVERAGE X (page 33)

P33 computes an average state vector and average variance on an element by element basis.

$$\hat{X}_{avg} = \hat{X}_{avg} + \frac{\hat{X}_k - \hat{X}_{avg}}{N}$$

$$\sigma^2_{avg} = \sigma^2_{avg} + \frac{(\hat{X}_k - \hat{X}_{avg})^2}{N} + \frac{1}{N}\left(\sigma^2_{avg} + \frac{(\hat{X}_k - \hat{X}_{avg})^2}{N}\right)$$

f) Measurement Update X pages (36-46), also Figure 2 (document page 16).

Introduction: For a position fix update the routine is entered twice; once with the North position error and once with the East position error. There are three arguments as inputs at each entrance:

1) KICK/NO KICK Marker
2) POS FIX/NO POS FIX Marker
3) Position Error N or E.

Generation of New State Vectors: Pages 36 through 42 are concerned with the generation of new state vectors.

Calculation of Residual, P36/MEASUREMENT UPDATE X through P36/$98

$$Res_{ik} = Y_i - M_i \ X_k$$

The residual combines the observation with each available state vector in turn. The residual is then checked to see if it is reasonable.

Verification of a valid residual

P36/$4

The residual is also incremented (and decremented) by integer (one lane) values and tested again for reasonableness. New state vectors are computed if the criterion is passed. This incrementing (decrementing) continues until the reasonableness test is failed. Thus several new state vectors could be generated from a single previous state vector. It is also possible that $\hat{X}_k$ may generate no new state vectors. Once the system has lane resolved, it is expected that only one state vector will be generated.

P36/$4+1

This test checks the residual against KQ.

$$|Res_{ik}|^2 < KQ_i$$

If yes then sequencing branches to P38/$1 where a new state vector is generated and validated. If NO then continue.

P36/$4+2

Is the KICK Marker and the POSITION FIX marker true? If Yes then, again, branch to P38/$1 where a new state vector is generated.

If no then continue.

P37/1 through P38/1

This page describes the incrementation and decrementation of the residual. This is done only with tracking filter fixes. For a position fix only the residual itself is used.

As a result of this loop either a new state vector is generated or:

If it is a position fix, and no new state vectors are generated and there are no old state vectors then a misfire is generated (see description P44/$83); if there are old state vectors then sequencing returns to P36/$17.

If it is a tracking filter fix then several conditions must be met to generate a misfire:

1) There are no old state vectors to process

2) There are no new state vectors generated

3) The accept limit is not less than $(.15 \text{ cycle})^2$ the accept limit is the value of Q from the compute BI & C subroutine

4) It is a good tracking filter measurement, and

5) It is not the base station.

P38/$1

At this point a residual is within acceptable limits, i.e., within the KQ criterion plus or minus N lanes. A new state vector will be generated and then checked for acceptability and uniqueness (against other new state vectors).

P38/$5

$$\hat{X}_k \text{ (new)} = \hat{X}_k \text{ (old)} + \begin{cases} b_i \, Res_{ik} & \text{if B code false} \\ Res_{ik} / \dfrac{1}{b_i} & \text{if B code true} \end{cases}$$

P38/$7+1

Did the 1st Position Error kick the system?

If so then it is known that the position fix error has caused an out of tolerance condition. Skip the 36 n mile test.

If not then continue.

P38/$7+2,3

Are the square of the first two elements of the state vector greater than 36 n miles? If so then the vector is rejected and the sequencing returns to the residual incrementation or decrementation loop.

If not then continue.

P39/$22+1 through P40/2

If this is the first new state vector generated at this call of the Measurement Update X routine, then it is unique and branching to P41/$10 skips the uniqueness test. If the current vector was not the first one generated then it will be checked against all currently existing new state vectors to verify uniqueness.

If it is not unique, i.e., if the difference between any corresponding element is not significant then the vector is discarded and sequencing returns to the residual inc/dec loop.

P40/$13

The new vector has been found unique with at least one other previously generated new state vector. It must be checked with all the new state vectors. The vector pointer is incremented. If there are more vectors then the vector under scrutiny must be checked against the others for uniqueness. Sequencing returns to P39/$11. If there are no more new vectors then sequencing continues.

P40/$13+2

If the vector storage area is full then declare a misfire. Otherwise continue with P41/$10.

P41/$10 through P41/$10+2

The state vector counter is incremented and the vector moved to a more permanent location.

The average state vector is updated and sequencing returns to the residual inc/dec loop to see if any other unique vectors can be generated from the original "old" state vector that generated the one just established.

P41/$2

This is the sequence described in P37/1. This point is reached as an exit from the residual inc/dec loop. All possible measurements from the old state vector have been made (one, in the case of a position fix).

P41/$2+1,2

If at this point there are old state vectors to be processed then sequencing returns to the residual inc/dec loop.

If there are no old state vectors then the program checks to see if there are any new state vectors.

If there have been new state vectors generated (the normal case) then sequencing continues to P42/1 where the covariance matrix P, is updated. The update of the P matrix will be described in the MEASUREMENT, UPDATE P subroutine.

Now, however, if there are no new state vectors, i.e., none have been generated, then a potential misfire situation is at hand and must be checked. Sequencing continues on P44/$83.

P42/\$19

If this is a position fix, then it is a misfire situation. The position fix has indicated a definite location for the system to within the specific lane. If the system position disagrees and the variances on both positions are small enough so that the positions are mutually exclusive, then a misfire situation is generated. Sequencing branches to P44/\$83.

P42/\$19+1

If, however, this is a tracking filter fix, then other checks must be made:

Is $Q < (.15 \text{ cycle})^2$

If so then set $Q = Q + (.15 \text{ cycle})^2$ and try again from the beginning; P36/MEAS. UPDATE X.

If not then continue (on P43/\$24)

P43/\$24,\$28,\$27

is $\sigma^2_{\dot{\phi}\dot{\phi}} < (.00031 \text{ cycle /sec})^2$

If not then this tracking filter fix is considered to be unworthy of further consideration.

Furthermore, the station check is set to zero. It is the station check which determines whether the system is confirmed. There are 24 indicators representing the "good measurements" from each station and frequency. If three stations have a history of good measurements on all three frequencies, since there was only one state vector, then the system is confirmed.

P43/\$25 through P43/\$25+2

If the tracking filter fix is good and it is not in the phase difference mode, or if it is phase difference and is not the base station then declare a misfire.

If the TF fix is good, is phase difference, and is the base station, then this measurement is ignored and processing continues to the next frequency. If no more frequencies to process, then exit Kalman without an update; i.e., use old state vectors.

Misfire:

<u>P44/$83</u>

If the phase rate error variance $\sigma^2_{\dot{\delta}\dot{\delta}}$ does not exceed (0.00031 cycle / sec)^2 the failure to pass the reasonableness criterion means that either 1) the present estimate of position is incorrect, or 2) the measurement is incorrect due to some other reason. In either case the filter is "opened up" by setting the two position variances to the larger value between their present value and the value at sigma squared kick (σ^2kick). The present measurement is disregarded and the filter then takes the next station pair. The misfire count is incremental to record this occurence.

g) Measurement Residue (page 47)

Computes Y - MX where Y is the measurement, M is the measurement matrix and X is a state vector.

h) MEASUREMENT UPDATE P (page 48)

<u>Covariance Matrix Generation</u>

If any new state vectors are generated by a measurement, a measurement updated covariance matrix is computed:

$$P(K) = P(K) - b_i M_i P(K) + \epsilon M_i^T b_i^T$$

If no new state vectors are generated by a measurement, the covariance matrix is not measurement updated.

i) ZERO ROW-COLUMN (page 49)

Will zero any row and column of a 9 x 9 matrix.

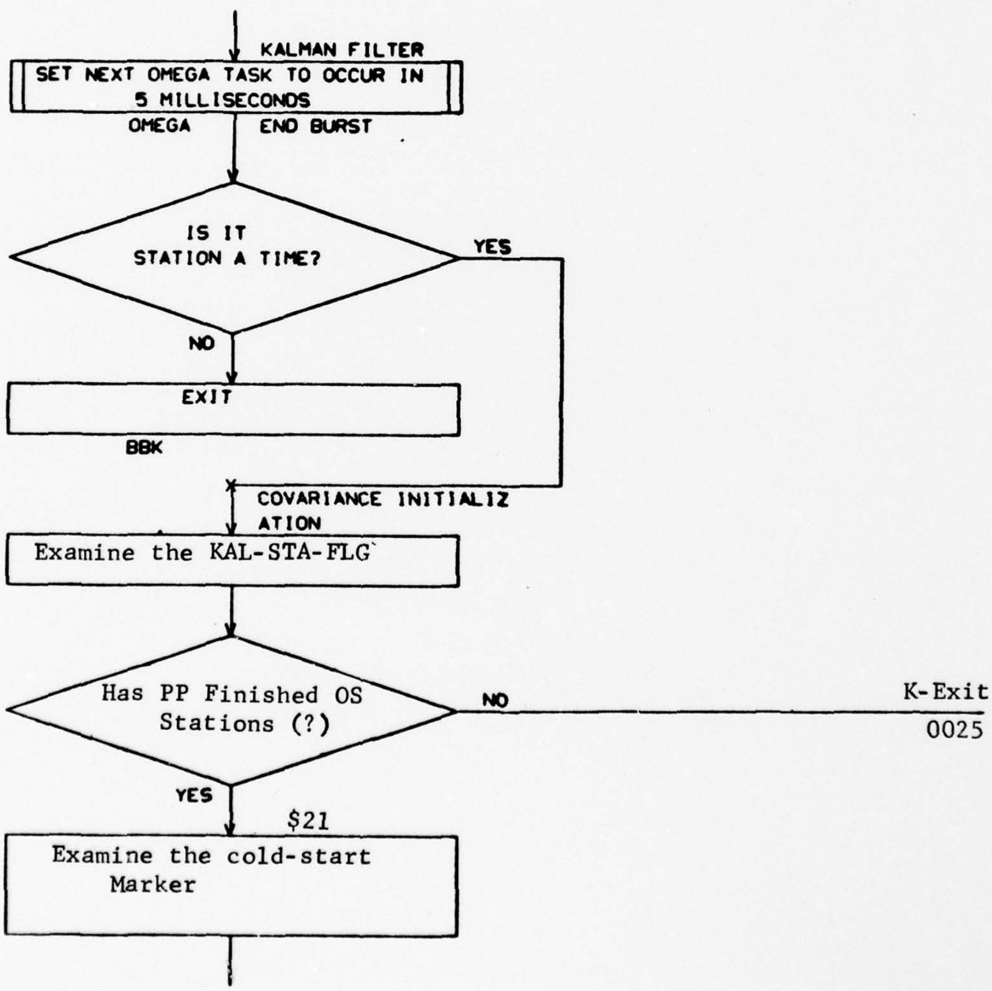
j) REGISTER SET UP (Page 50)

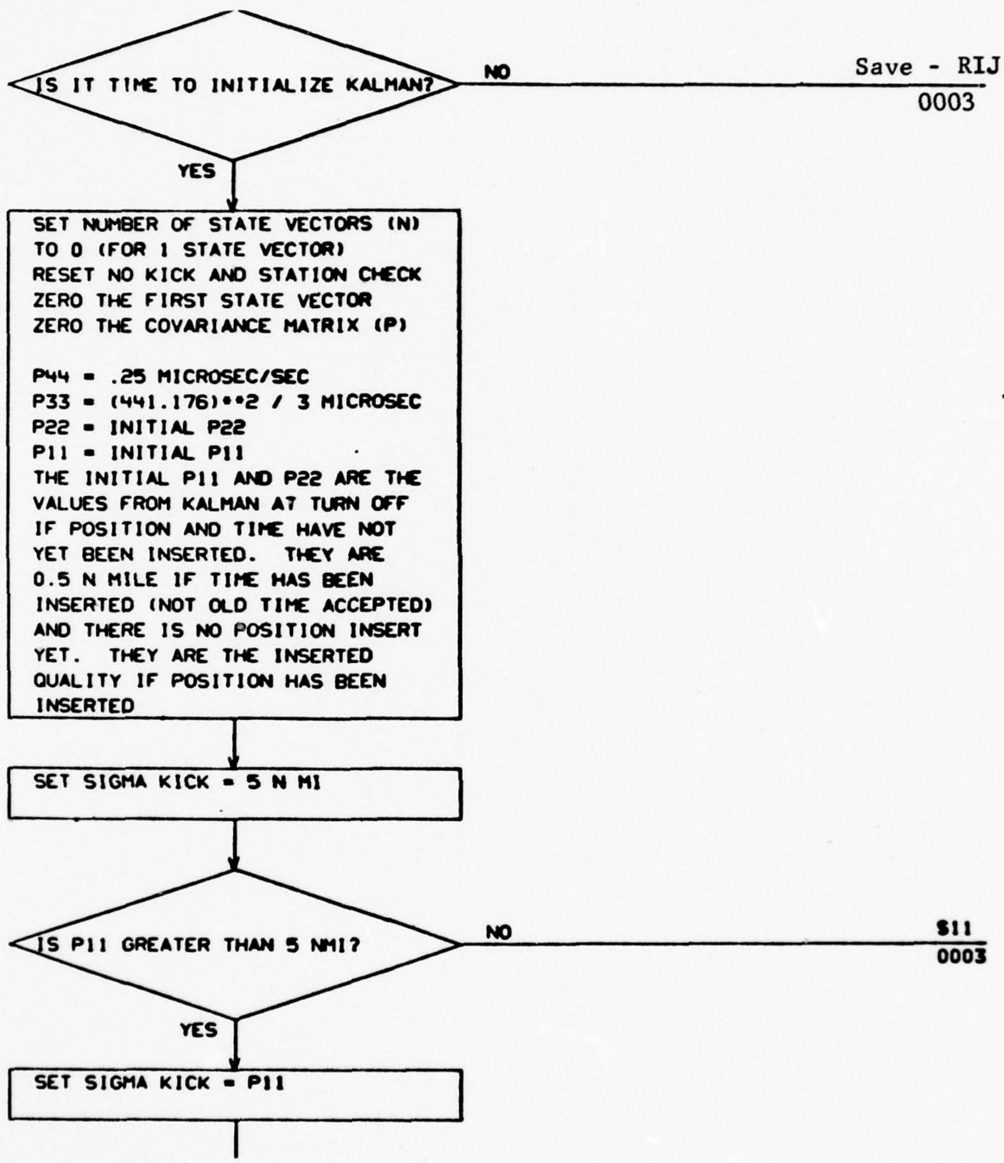
Creates 14 registers and sets up common pointers.

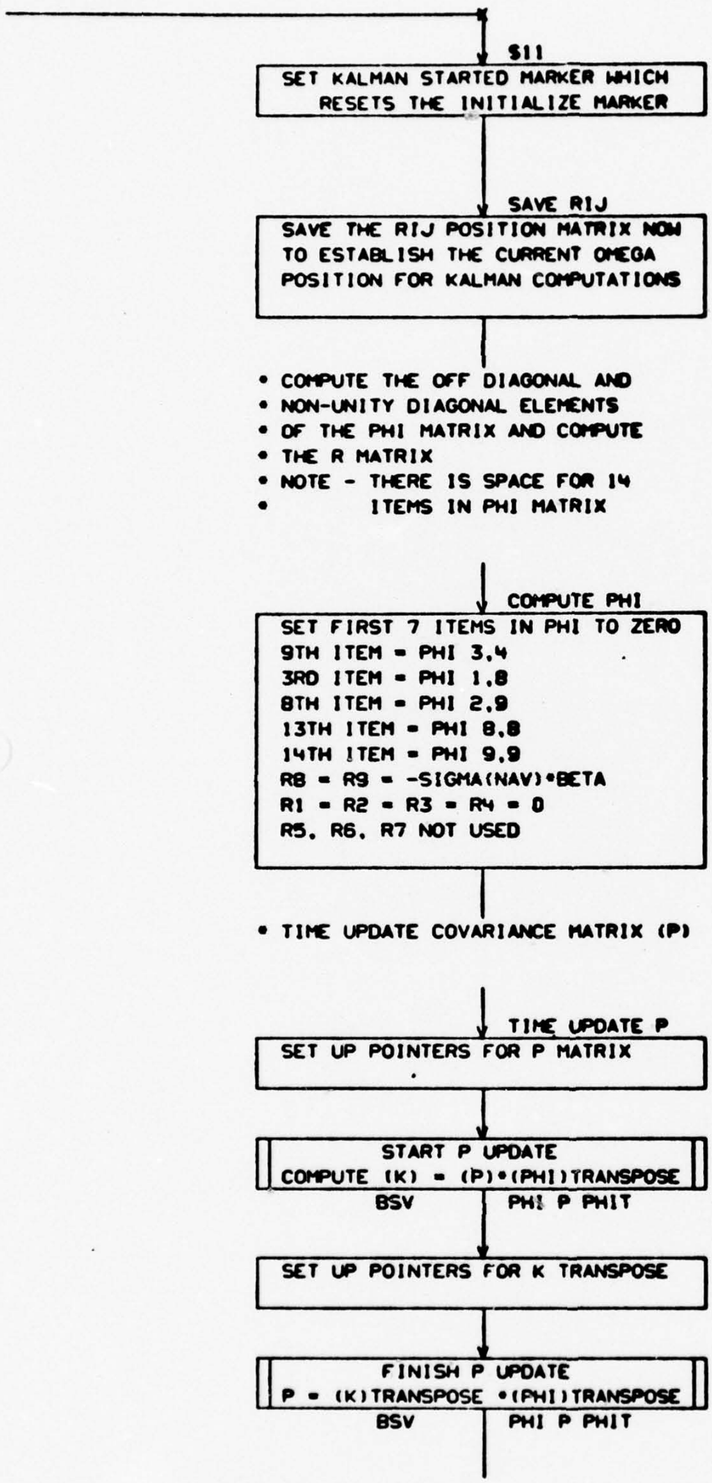
3.2 FLOW DIAGRAMS

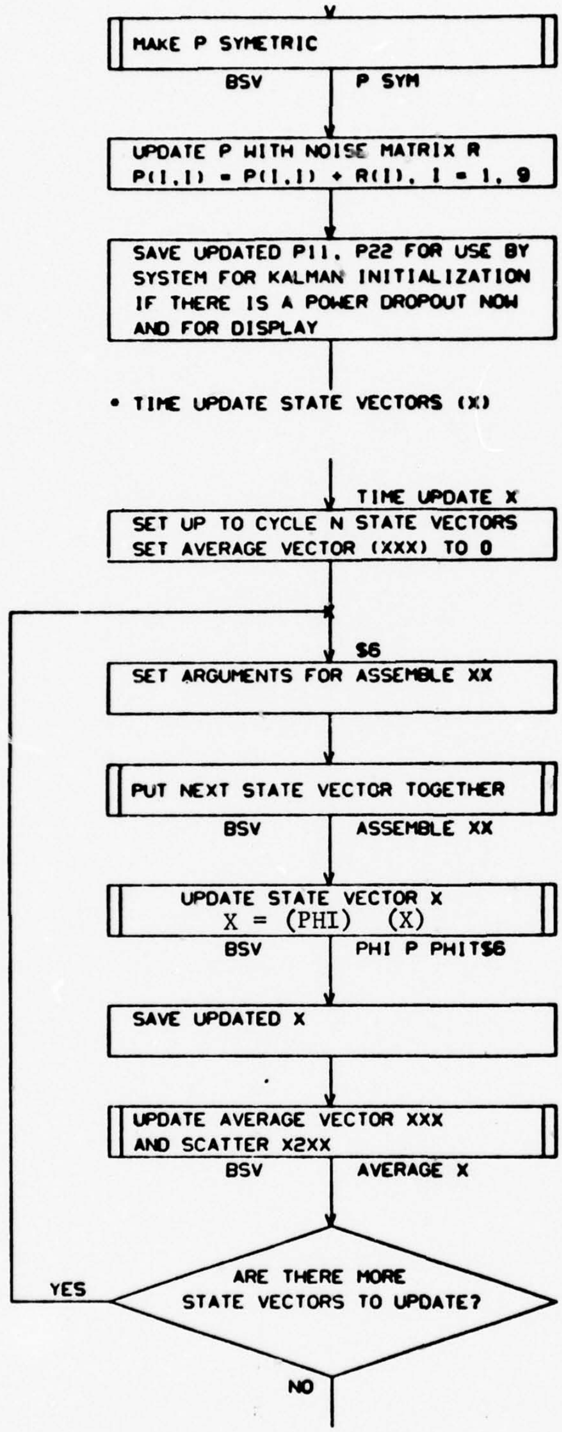
The Kalman Filter subprogram flow charts are presented on the following pages.

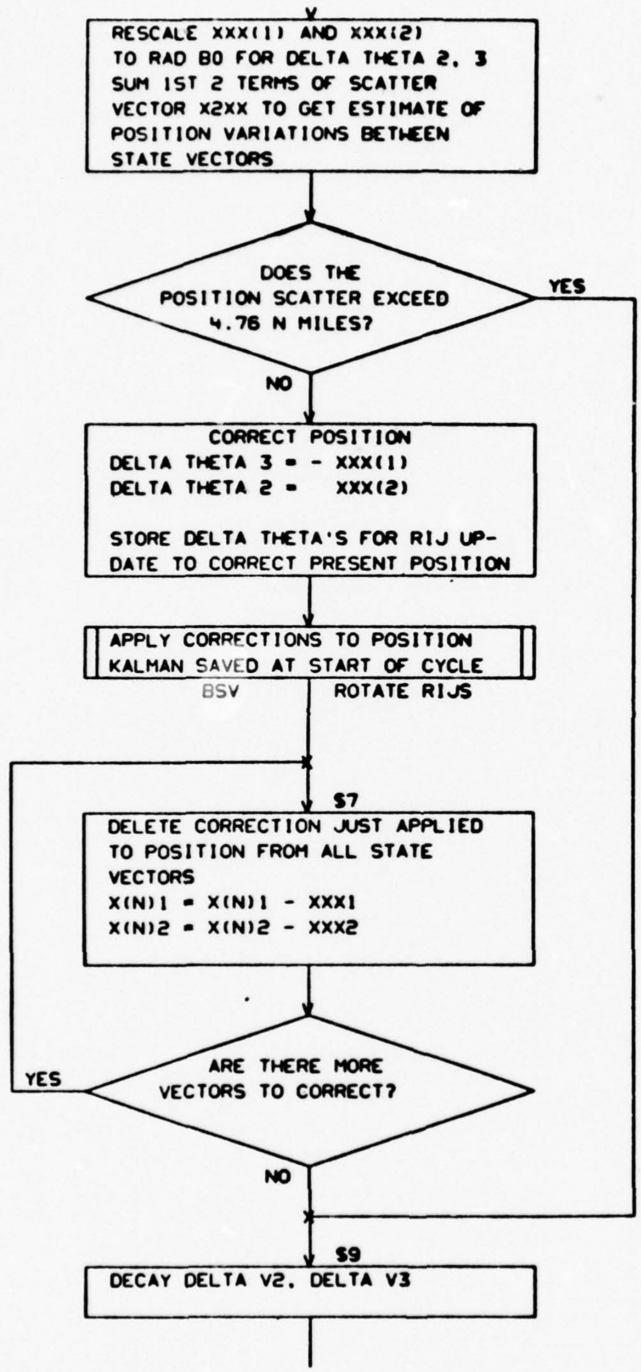
```
*
*                               KALMAN FILTER
*
* THIS PROGRAM PROCESSES TRACKING FILTER MEASUREMENTS AND POSITION FIXES
* TO GENERATE ESTIMATES OF SYSTEM ERRORS.  IT IS AN OMEGA TASK THAT IS
* ENTERED 5 MILLISECONDS BEFORE END BURST.  THIS PROGRAM ONLY CYCLES
* WHEN THE STATION COUNTER IS 0 (STATION A).  IT HAS BEEN SYNCHRONIZED
* WITH THE NON OMEGA TASK ROUTINES IN SUCH A WAY THAT RIJ UPDATE OCCURS
* 5 MILLISECONDS BEFORE KALMAN.  FIVE MILLISECONDS AFTER KALMAN IS INI-
* TIATED THE END BURST/TRACKING FILTER ROUTINES WILL INTERRUPT KALMAN SO
* THAT ALL TRACKING FILTERS WILL BE TIME UPDATED TO THE END BURST TIME.
* THIS RESULTS IN THE RIJ, KALMAN AND TRACKING FILTER UPDATES OCCURING
* WITHIN A 10 MILLISECOND PERIOD.  FOR THIS TIMING TO BE CORRECT KALMAN
* MUST NOT READ ANY TRACKING FILTER DATA IN THE 5 MILLISECONDS AVAILABLE
* BEFORE THE END BURST INTERRUPT.
*
```

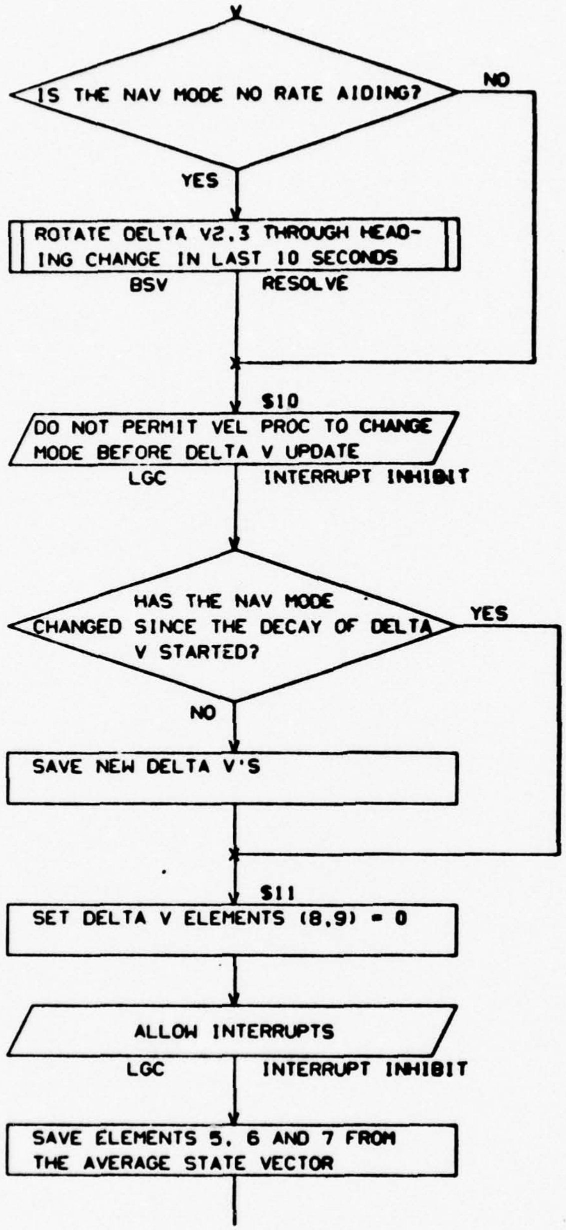


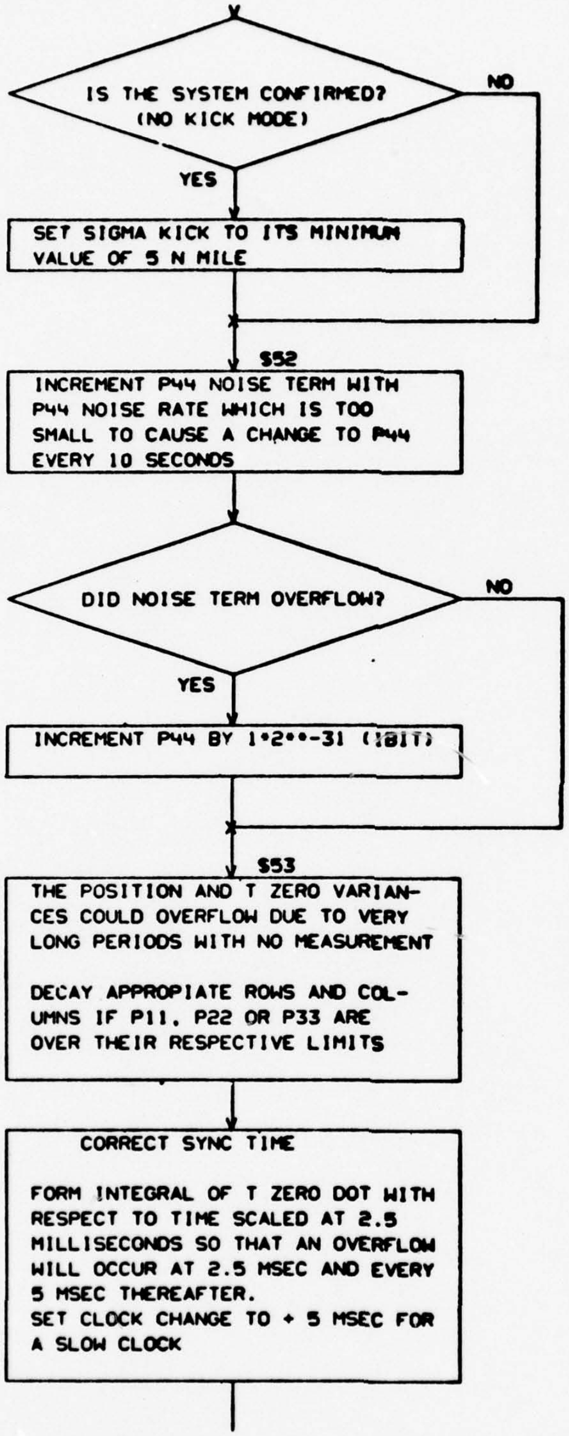

IS IT TIME TO INITIALIZE KALMAN?
NO
Save - RIJ
0003
YES
SET NUMBER OF STATE VECTORS (N) TO 0 (FOR 1 STATE VECTOR)
RESET NO KICK AND STATION CHECK
ZERO THE FIRST STATE VECTOR
ZERO THE COVARIANCE MATRIX (P)
P44 = .25 MICROSEC/SEC
P33 = (441.176)**2 / 3 MICROSEC
P22 = INITIAL P22
P11 = INITIAL P11
THE INITIAL P11 AND P22 ARE THE VALUES FROM KALMAN AT TURN OFF IF POSITION AND TIME HAVE NOT YET BEEN INSERTED. THEY ARE 0.5 N MILE IF TIME HAS BEEN INSERTED (NOT OLD TIME ACCEPTED) AND THERE IS NO POSITION INSERT YET. THEY ARE THE INSERTED QUALITY IF POSITION HAS BEEN INSERTED
SET SIGMA KICK = 5 N MI
IS P11 GREATER THAN 5 NMI?
NO
S11
0003
YES
SET SIGMA KICK = P11

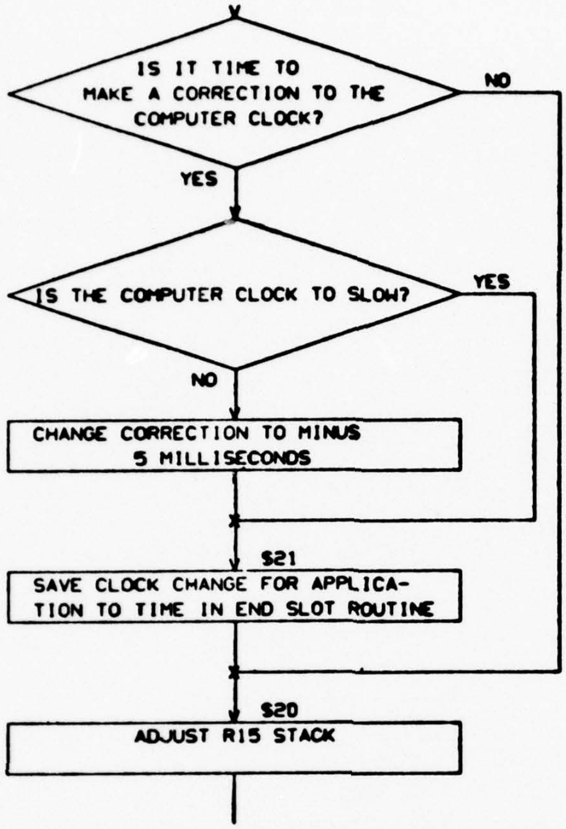

S11
SET KALMAN STARTED MARKER WHICH RESETS THE INITIALIZE MARKER
SAVE RIJ
SAVE THE RIJ POSITION MATRIX NOW TO ESTABLISH THE CURRENT OMEGA POSITION FOR KALMAN COMPUTATIONS
• COMPUTE THE OFF DIAGONAL AND
• NON-UNITY DIAGONAL ELEMENTS
• OF THE PHI MATRIX AND COMPUTE
• THE R MATRIX
• NOTE - THERE IS SPACE FOR 14
• ITEMS IN PHI MATRIX
COMPUTE PHI
SET FIRST 7 ITEMS IN PHI TO ZERO
9TH ITEM = PHI 3,4
3RD ITEM = PHI 1,8
8TH ITEM = PHI 2,9
13TH ITEM = PHI 8,8
14TH ITEM = PHI 9,9
R8 = R9 = -SIGMA(NAV)*BETA
R1 = R2 = R3 = R4 = 0
R5, R6, R7 NOT USED
• TIME UPDATE COVARIANCE MATRIX (P)
TIME UPDATE P
SET UP POINTERS FOR P MATRIX
START P UPDATE
COMPUTE (K) = (P)*(PHI)TRANSPOSE
BSV
PHI P PHIT
SET UP POINTERS FOR K TRANSPOSE
FINISH P UPDATE
P = (K)TRANSPOSE *(PHI)TRANSPOSE
BSV
PHI P PHIT


MAKE P SYMETRIC
BSV
P SYM
UPDATE P WITH NOISE MATRIX R
P(I,I) = P(I,I) + R(I), I = 1, 9
SAVE UPDATED P11, P22 FOR USE BY SYSTEM FOR KALMAN INITIALIZATION IF THERE IS A POWER DROPOUT NOW AND FOR DISPLAY
• TIME UPDATE STATE VECTORS (X)
TIME UPDATE X
SET UP TO CYCLE N STATE VECTORS
SET AVERAGE VECTOR (XXX) TO 0
$6
SET ARGUMENTS FOR ASSEMBLE XX
PUT NEXT STATE VECTOR TOGETHER
BSV
ASSEMBLE XX
UPDATE STATE VECTOR X
X = (PHI) (X)
BSV
PHI P PHIT$6
SAVE UPDATED X
UPDATE AVERAGE VECTOR XXX AND SCATTER X2XX
BSV
AVERAGE X
ARE THERE MORE STATE VECTORS TO UPDATE?
YES
NO

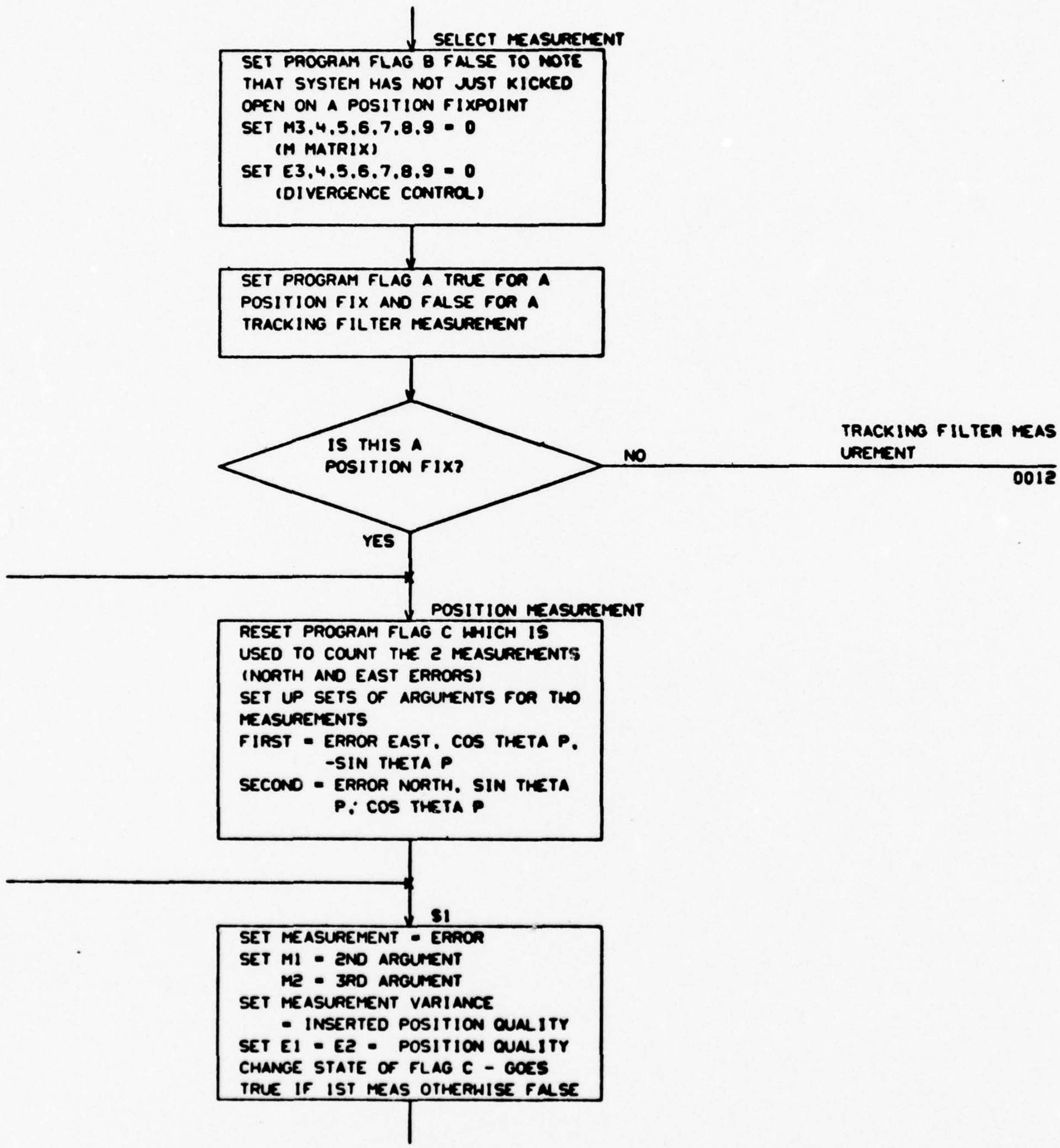

RESCALE XXX(1) AND XXX(2)
TO RAD B0 FOR DELTA THETA 2, 3
SUM 1ST 2 TERMS OF SCATTER
VECTOR X2XX TO GET ESTIMATE OF
POSITION VARIATIONS BETWEEN
STATE VECTORS
DOES THE
POSITION SCATTER EXCEED
4.76 N MILES?
YES
NO
CORRECT POSITION
DELTA THETA 3 = - XXX(1)
DELTA THETA 2 = XXX(2)
STORE DELTA THETA'S FOR RIJ UP-
DATE TO CORRECT PRESENT POSITION
APPLY CORRECTIONS TO POSITION
KALMAN SAVED AT START OF CYCLE
BSV
ROTATE RIJS
S7
DELETE CORRECTION JUST APPLIED
TO POSITION FROM ALL STATE
VECTORS
X(N)1 = X(N)1 - XXX1
X(N)2 = X(N)2 - XXX2
ARE THERE MORE
VECTORS TO CORRECT?
YES
NO
S9
DECAY DELTA V2, DELTA V3

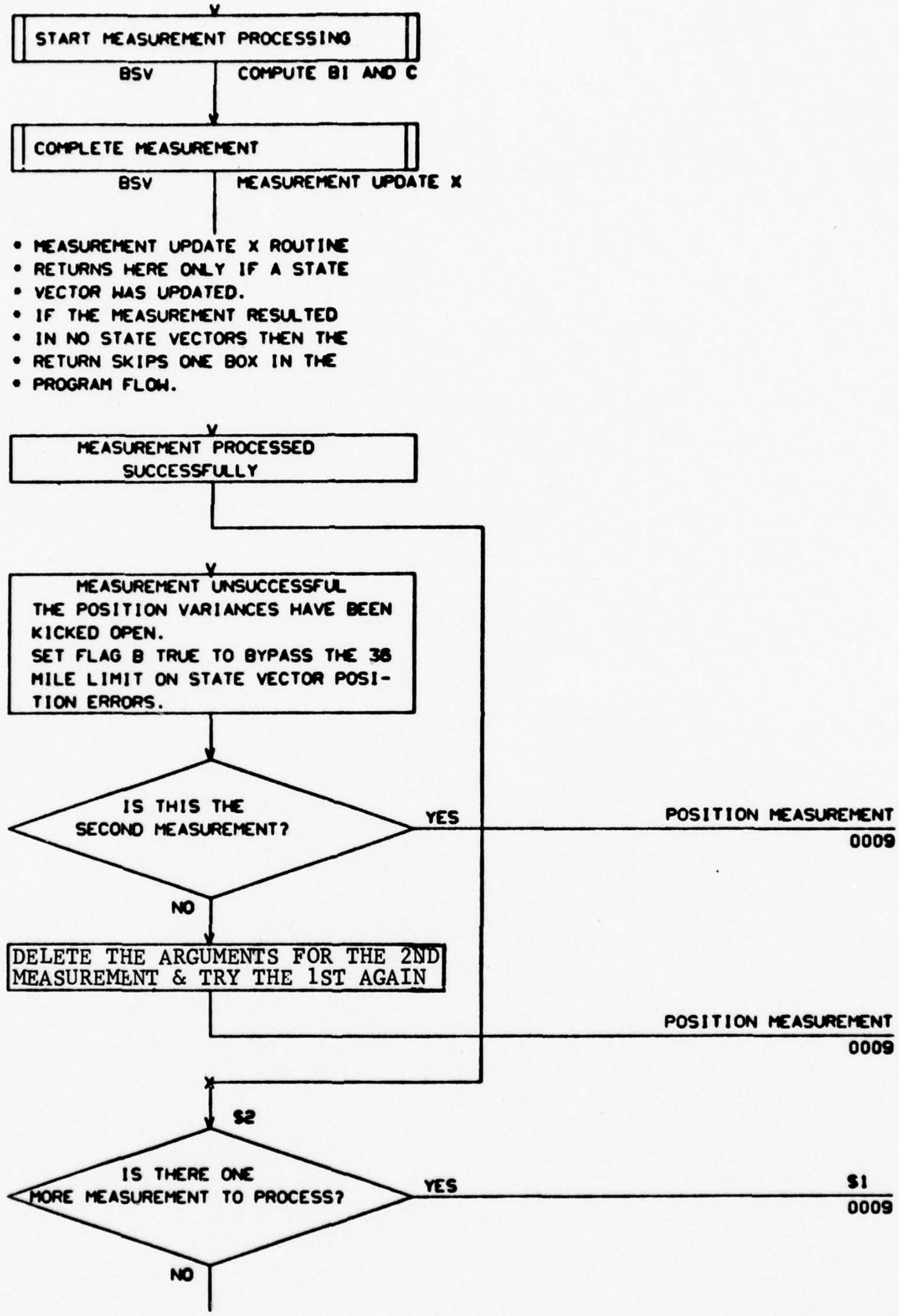

IS THE NAV MODE NO RATE AIDING?
NO
YES
ROTATE DELTA V2,3 THROUGH HEADING CHANGE IN LAST 10 SECONDS
BSV
RESOLVE
$10
DO NOT PERMIT VEL PROC TO CHANGE MODE BEFORE DELTA V UPDATE
LGC
INTERRUPT INHIBIT
HAS THE NAV MODE CHANGED SINCE THE DECAY OF DELTA V STARTED?
YES
NO
SAVE NEW DELTA V'S
$11
SET DELTA V ELEMENTS (8,9) = 0
ALLOW INTERRUPTS
LGC
INTERRUPT INHIBIT
SAVE ELEMENTS 5, 6 AND 7 FROM THE AVERAGE STATE VECTOR

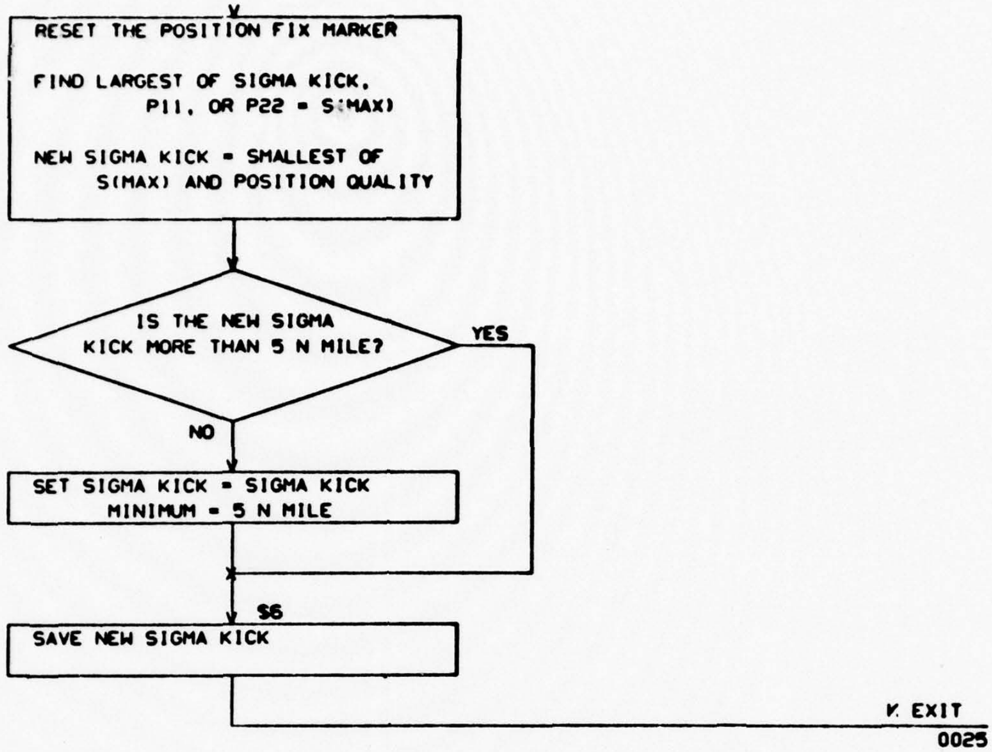

IS THE SYSTEM CONFIRMED?
(NO KICK MODE)
NO
YES
SET SIGMA KICK TO ITS MINIMUM VALUE OF 5 N MILE
S52
INCREMENT P44 NOISE TERM WITH P44 NOISE RATE WHICH IS TOO SMALL TO CAUSE A CHANGE TO P44 EVERY 10 SECONDS
DID NOISE TERM OVERFLOW?
NO
YES
INCREMENT P44 BY 1*2**-31 (1BIT)
S53
THE POSITION AND T ZERO VARIANCES COULD OVERFLOW DUE TO VERY LONG PERIODS WITH NO MEASUREMENT
DECAY APPROPIATE ROWS AND COLUMNS IF P11, P22 OR P33 ARE OVER THEIR RESPECTIVE LIMITS
CORRECT SYNC TIME
FORM INTEGRAL OF T ZERO DOT WITH RESPECT TO TIME SCALED AT 2.5 MILLISECONDS SO THAT AN OVERFLOW WILL OCCUR AT 2.5 MSEC AND EVERY 5 MSEC THEREAFTER.
SET CLOCK CHANGE TO + 5 MSEC FOR A SLOW CLOCK


IS IT TIME TO MAKE A CORRECTION TO THE COMPUTER CLOCK?
NO
YES
IS THE COMPUTER CLOCK TO SLOW?
YES
NO
CHANGE CORRECTION TO MINUS 5 MILLISECONDS
$21
SAVE CLOCK CHANGE FOR APPLICATION TO TIME IN END SLOT ROUTINE
$20
ADJUST R15 STACK

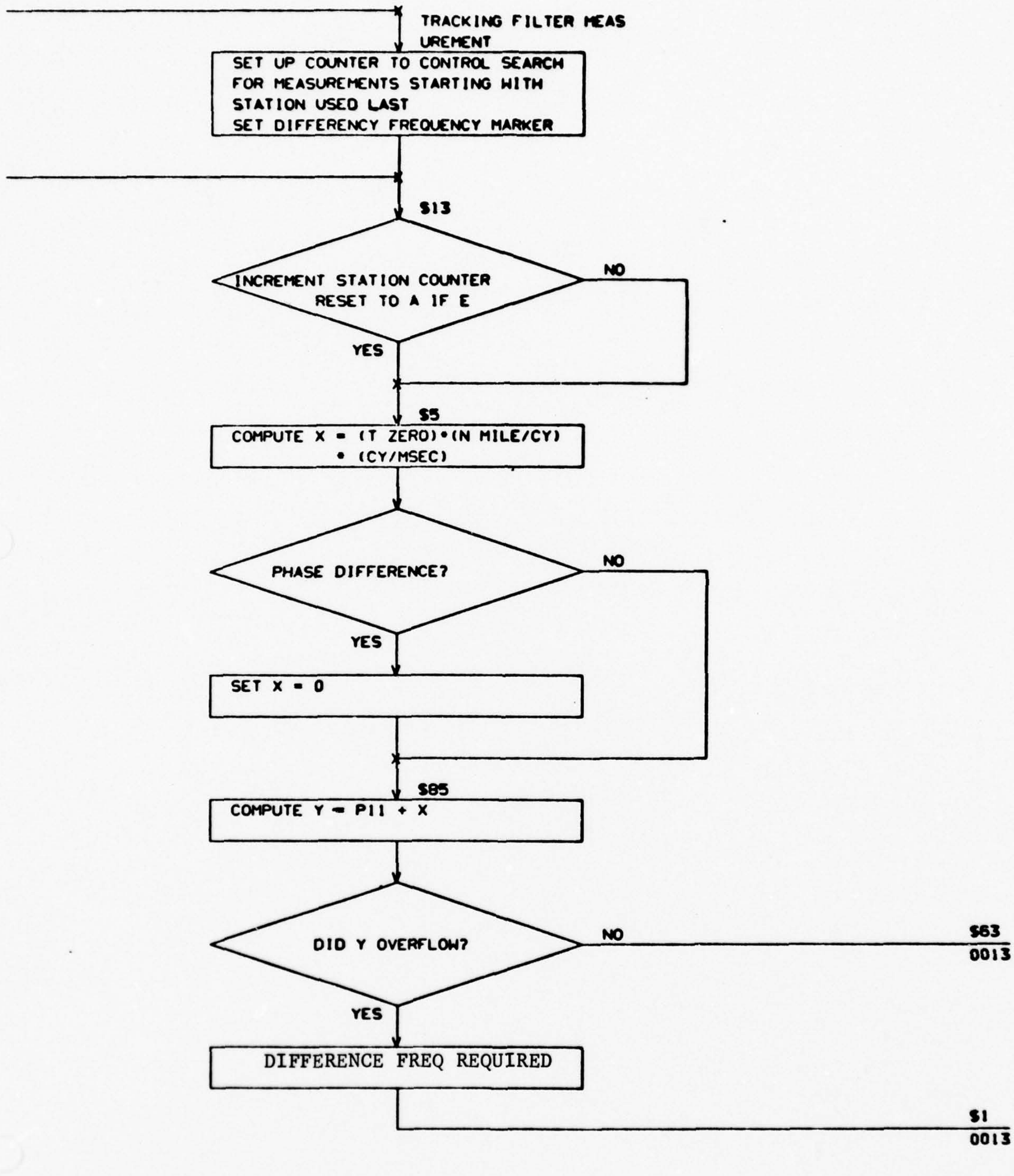
- SELECT MEASUREMENT TYPE - TAKE
- POSITION FIX IF AVAILABLE
- OTHERWISE TRY FOR A TRACKING
- FILTER MEASUREMENT

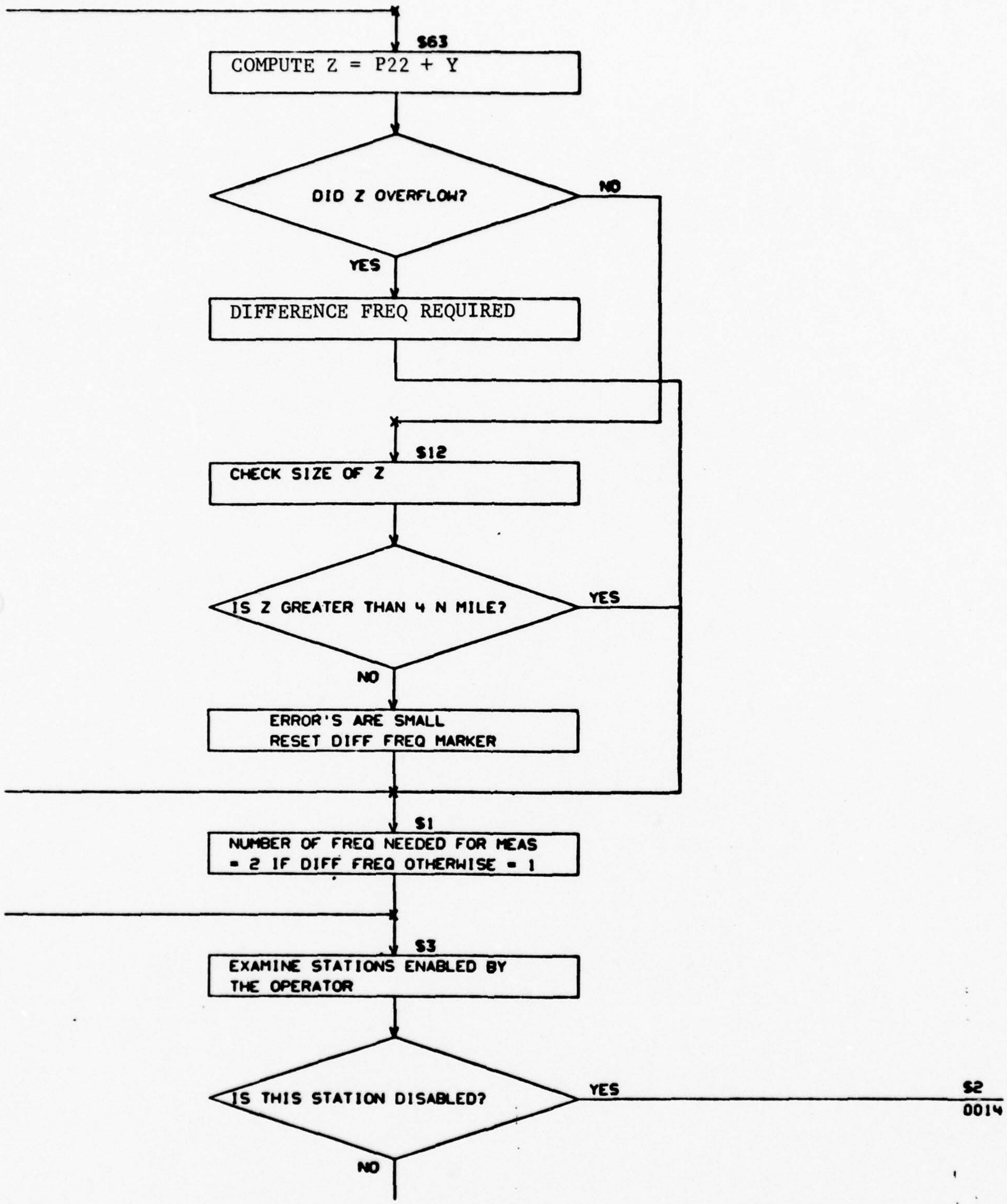



START MEASUREMENT PROCESSING
BSV
COMPUTE BI AND C
COMPLETE MEASUREMENT
BSV
MEASUREMENT UPDATE X
• MEASUREMENT UPDATE X ROUTINE
• RETURNS HERE ONLY IF A STATE
• VECTOR WAS UPDATED.
• IF THE MEASUREMENT RESULTED
• IN NO STATE VECTORS THEN THE
• RETURN SKIPS ONE BOX IN THE
• PROGRAM FLOW.
MEASUREMENT PROCESSED SUCCESSFULLY
MEASUREMENT UNSUCCESSFUL
THE POSITION VARIANCES HAVE BEEN KICKED OPEN.
SET FLAG B TRUE TO BYPASS THE 38 MILE LIMIT ON STATE VECTOR POSITION ERRORS.
IS THIS THE SECOND MEASUREMENT?
YES
POSITION MEASUREMENT
0009
NO
DELETE THE ARGUMENTS FOR THE 2ND MEASUREMENT & TRY THE 1ST AGAIN
POSITION MEASUREMENT
0009
S2
IS THERE ONE MORE MEASUREMENT TO PROCESS?
YES
S1
0009
NO

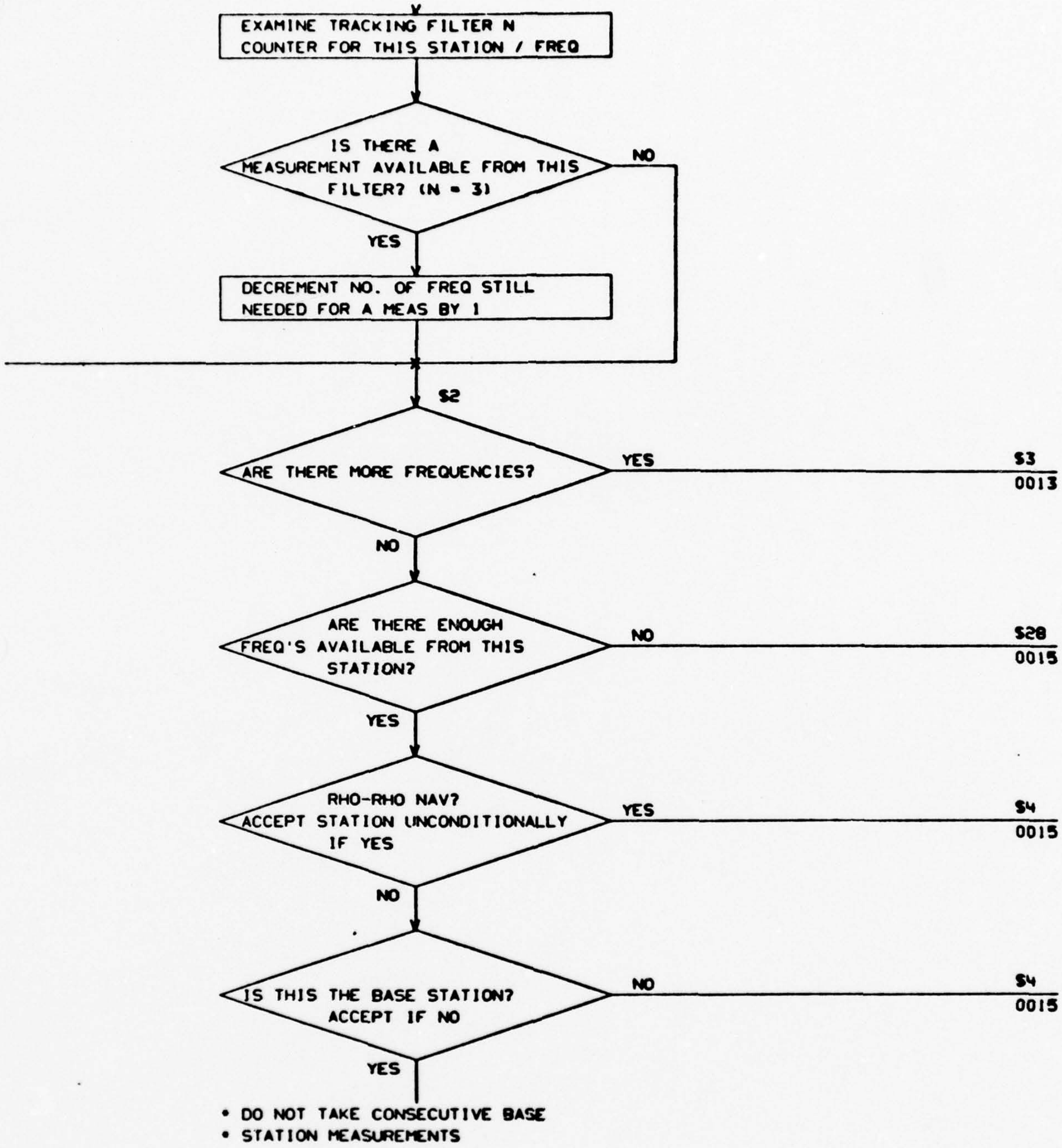

RESET THE POSITION FIX MARKER
FIND LARGEST OF SIGMA KICK, P11, OR P22 = S(MAX)
NEW SIGMA KICK = SMALLEST OF S(MAX) AND POSITION QUALITY
IS THE NEW SIGMA KICK MORE THAN 5 N MILE?
YES
NO
SET SIGMA KICK = SIGMA KICK MINIMUM = 5 N MILE
S6
SAVE NEW SIGMA KICK
EXIT
0025

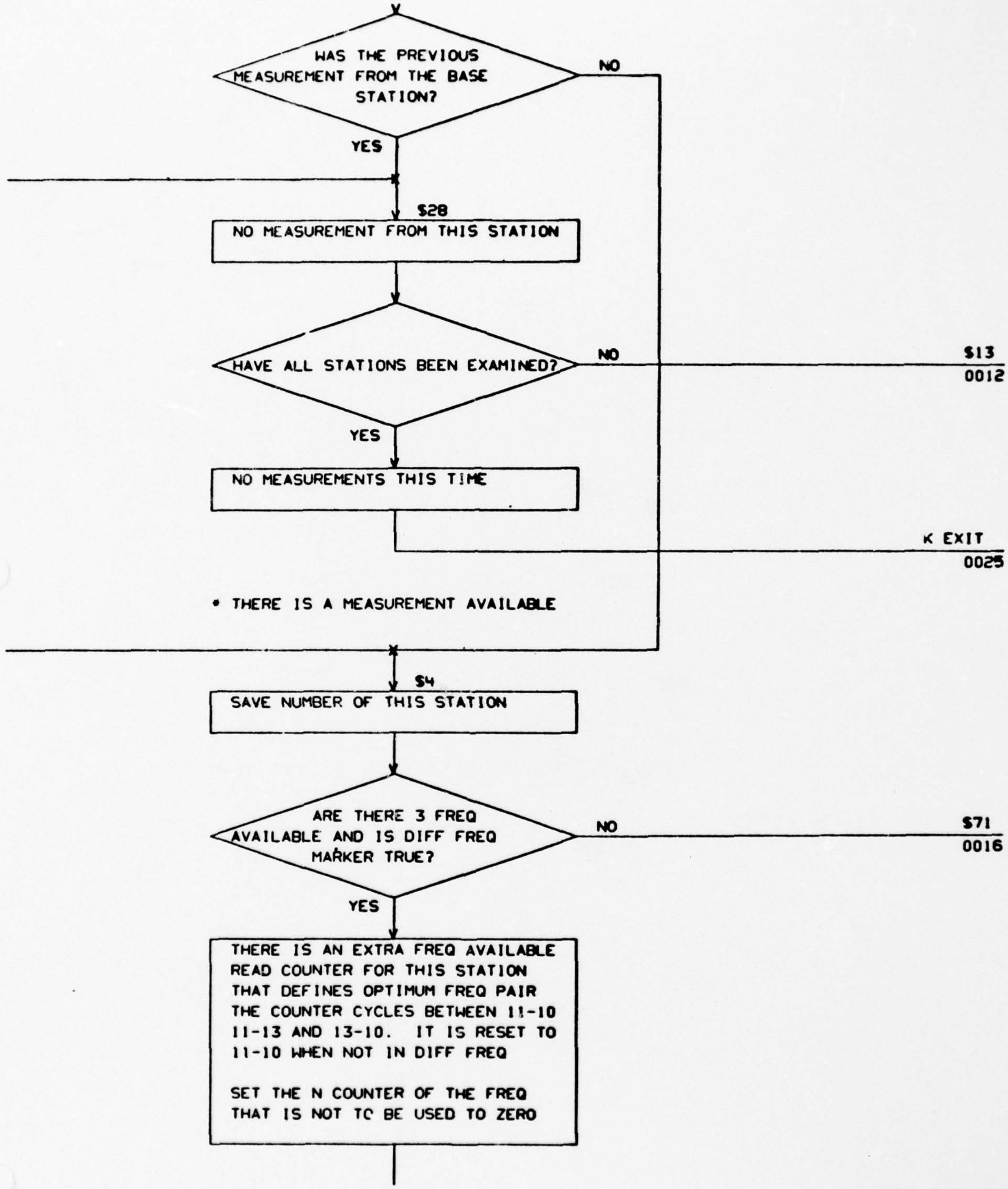
* LOOK FOR MEASUREMENT FROM 1 OR
* MORE FILTERS FOR ANY STATION



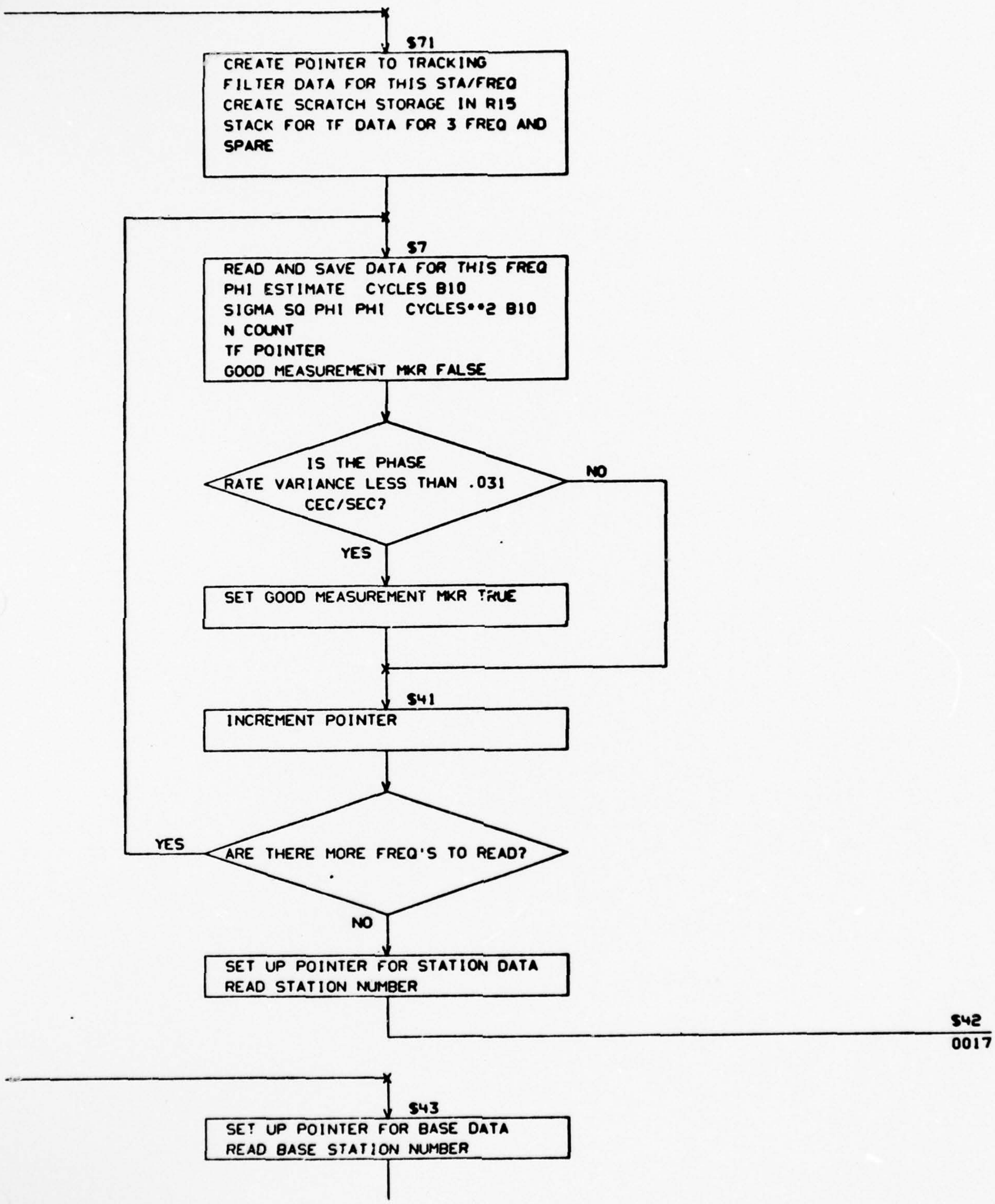


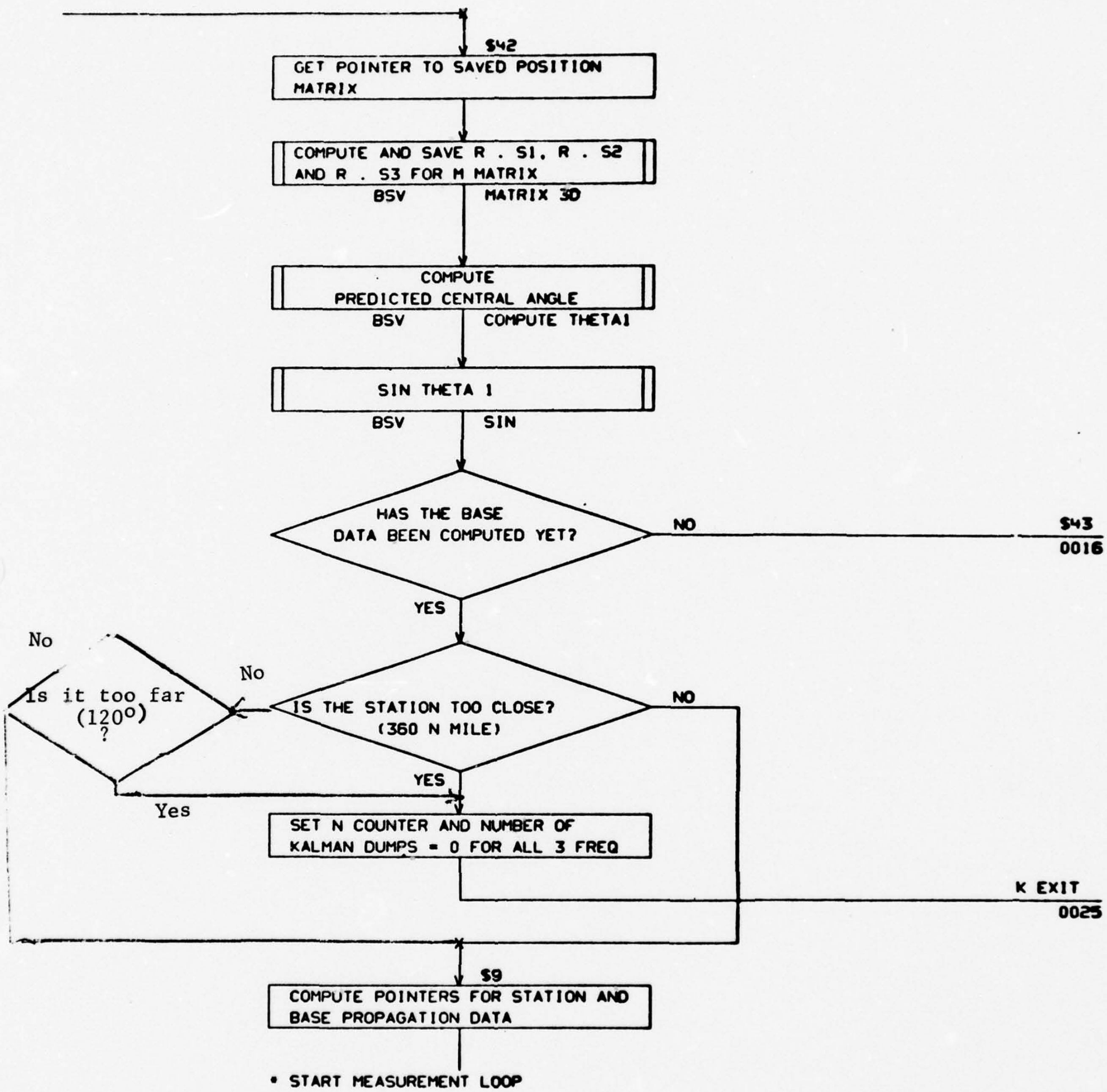
S63
COMPUTE Z = P22 + Y
DID Z OVERFLOW?
NO
YES
DIFFERENCE FREQ REQUIRED
S12
CHECK SIZE OF Z
IS Z GREATER THAN 4 N MILE?
YES
NO
ERROR'S ARE SMALL
RESET DIFF FREQ MARKER
S1
NUMBER OF FREQ NEEDED FOR MEAS
= 2 IF DIFF FREQ OTHERWISE = 1
S3
EXAMINE STATIONS ENABLED BY
THE OPERATOR
IS THIS STATION DISABLED?
YES
S2
0014
NO

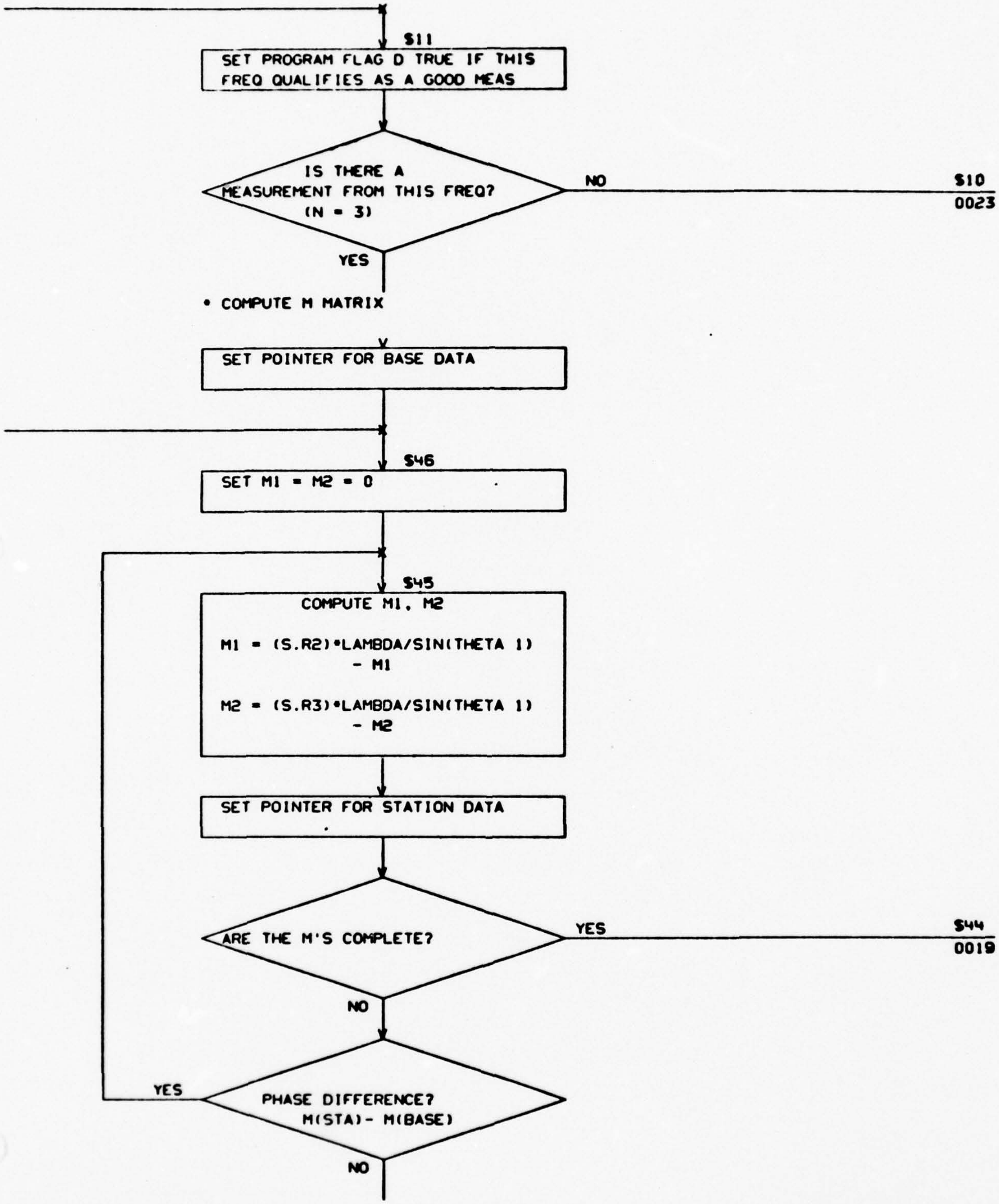

EXAMINE TRACKING FILTER N
COUNTER FOR THIS STATION / FREQ
IS THERE A
MEASUREMENT AVAILABLE FROM THIS
FILTER? (N = 3)
NO
YES
DECREMENT NO. OF FREQ STILL
NEEDED FOR A MEAS BY 1
$2
ARE THERE MORE FREQUENCIES?
YES
$3
0013
NO
ARE THERE ENOUGH
FREQ'S AVAILABLE FROM THIS
STATION?
NO
$28
0015
YES
RHO-RHO NAV?
ACCEPT STATION UNCONDITIONALLY
IF YES
YES
$4
0015
NO
IS THIS THE BASE STATION?
ACCEPT IF NO
NO
$4
0015
YES
• DO NOT TAKE CONSECUTIVE BASE
• STATION MEASUREMENTS

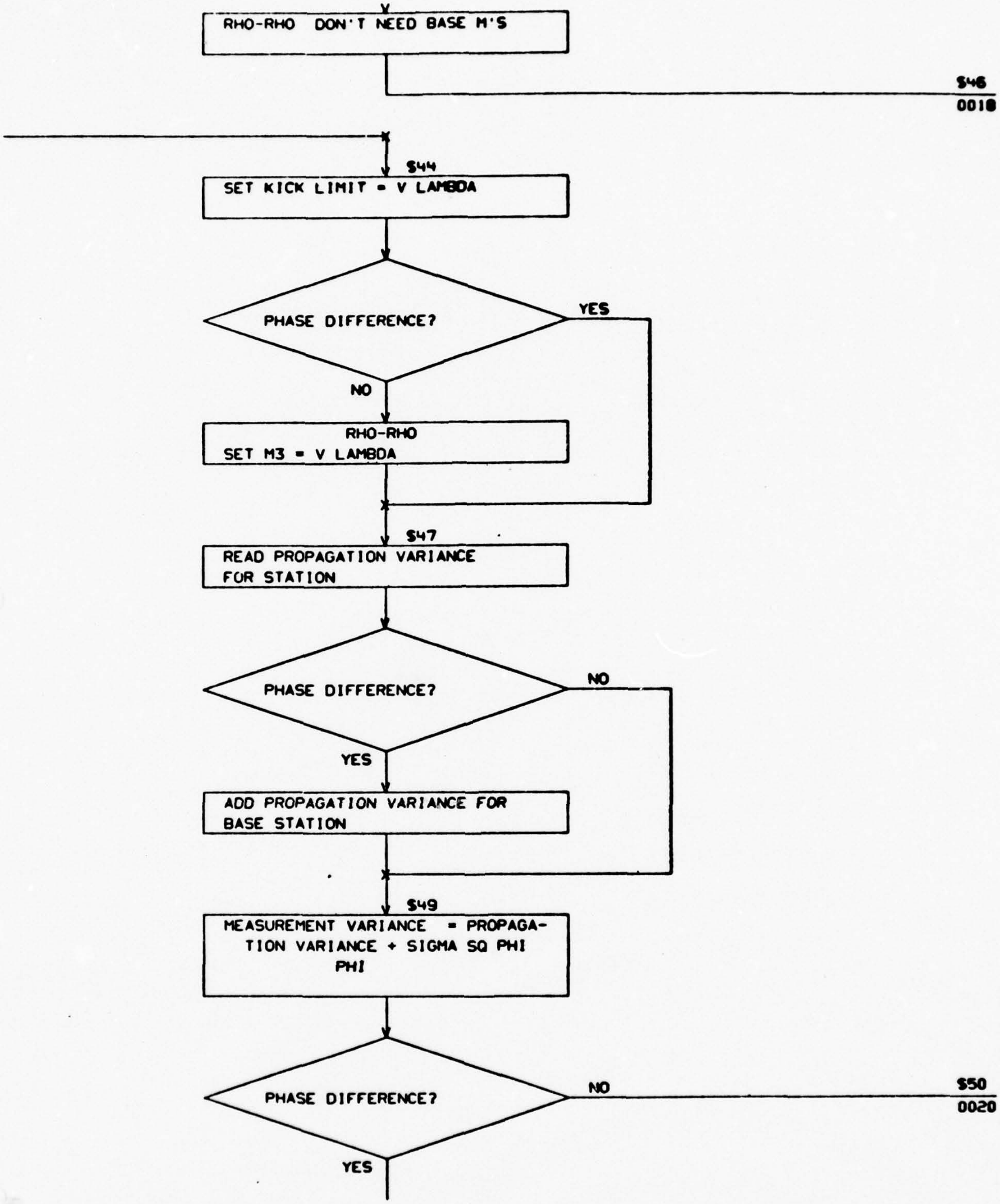


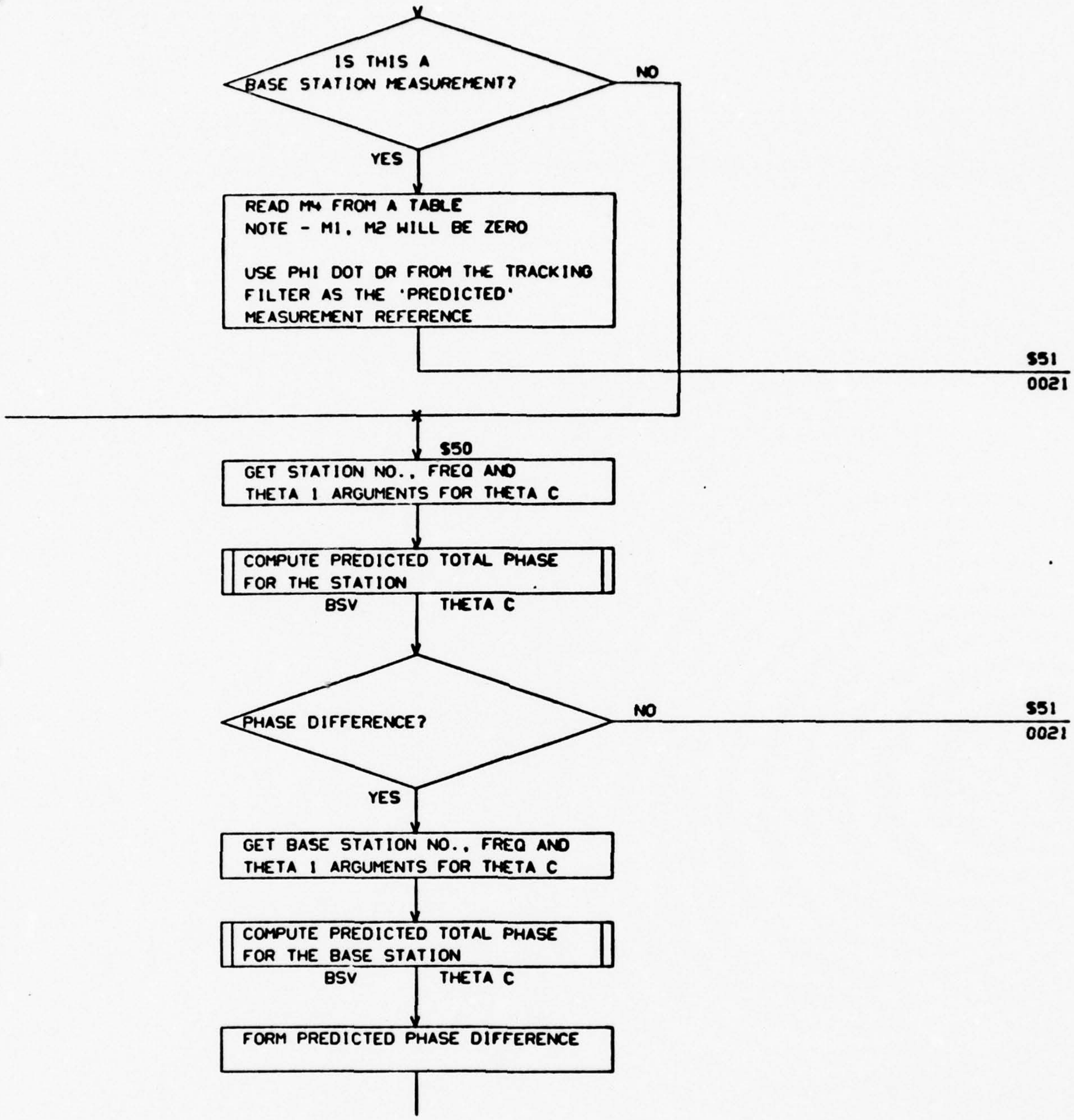
WAS THE PREVIOUS MEASUREMENT FROM THE BASE STATION?
NO
YES
$28
NO MEASUREMENT FROM THIS STATION
HAVE ALL STATIONS BEEN EXAMINED?
NO
$13
0012
YES
NO MEASUREMENTS THIS TIME
K EXIT
0025
* THERE IS A MEASUREMENT AVAILABLE
$4
SAVE NUMBER OF THIS STATION
ARE THERE 3 FREQ AVAILABLE AND IS DIFF FREQ MARKER TRUE?
NO
$71
0016
YES
THERE IS AN EXTRA FREQ AVAILABLE
READ COUNTER FOR THIS STATION
THAT DEFINES OPTIMUM FREQ PAIR
THE COUNTER CYCLES BETWEEN 11-10
11-13 AND 13-10. IT IS RESET TO
11-10 WHEN NOT IN DIFF FREQ
SET THE N COUNTER OF THE FREQ
THAT IS NOT TC BE USED TO ZERO

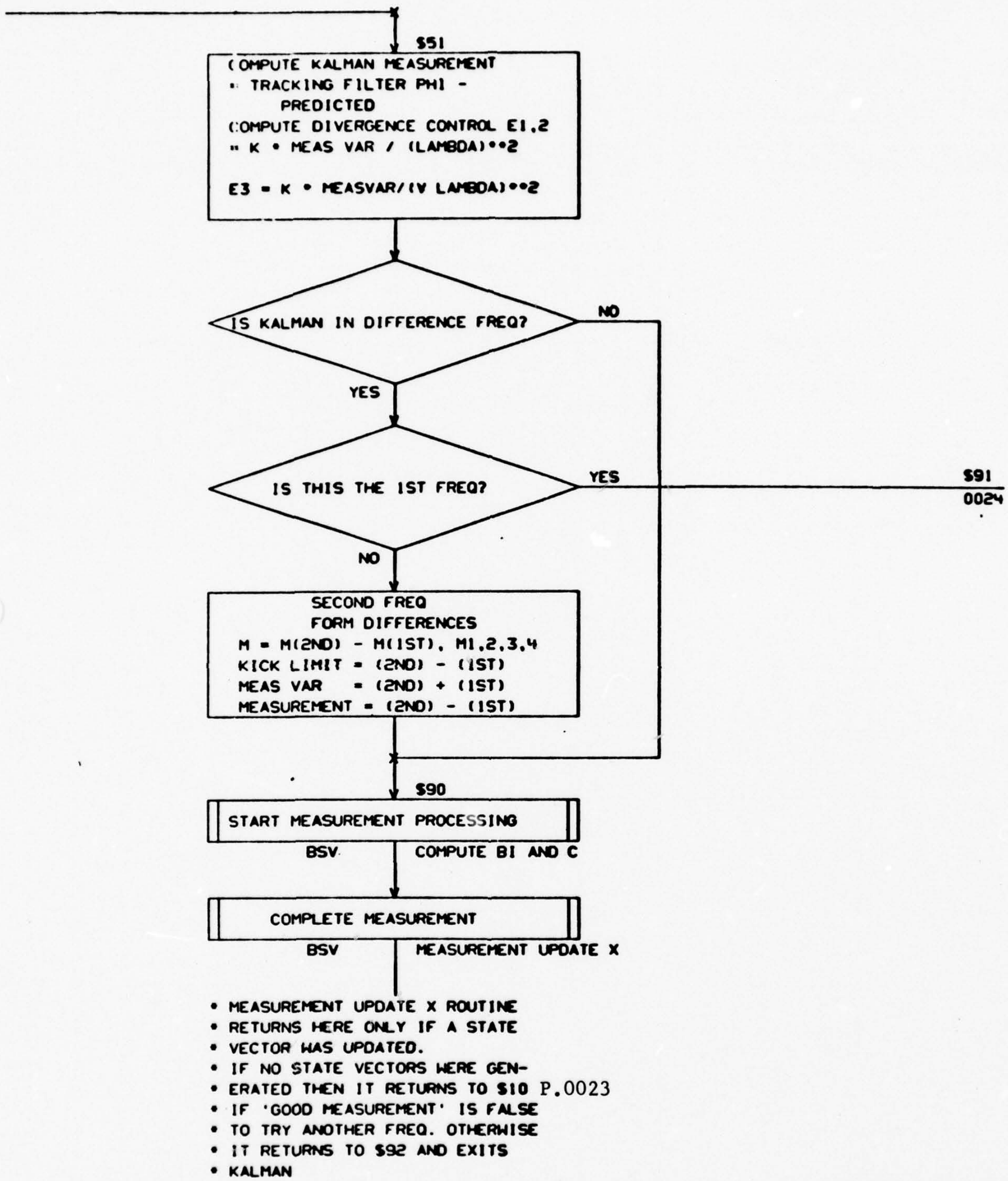

$71
CREATE POINTER TO TRACKING FILTER DATA FOR THIS STA/FREQ
CREATE SCRATCH STORAGE IN R15 STACK FOR TF DATA FOR 3 FREQ AND SPARE
$7
READ AND SAVE DATA FOR THIS FREQ
PHI ESTIMATE CYCLES B10
SIGMA SQ PHI PHI CYCLES**2 B10
N COUNT
TF POINTER
GOOD MEASUREMENT MKR FALSE
IS THE PHASE RATE VARIANCE LESS THAN .031 CEC/SEC?
NO
YES
SET GOOD MEASUREMENT MKR TRUE
$41
INCREMENT POINTER
ARE THERE MORE FREQ'S TO READ?
YES
NO
SET UP POINTER FOR STATION DATA
READ STATION NUMBER
$42
0017
$43
SET UP POINTER FOR BASE DATA
READ BASE STATION NUMBER

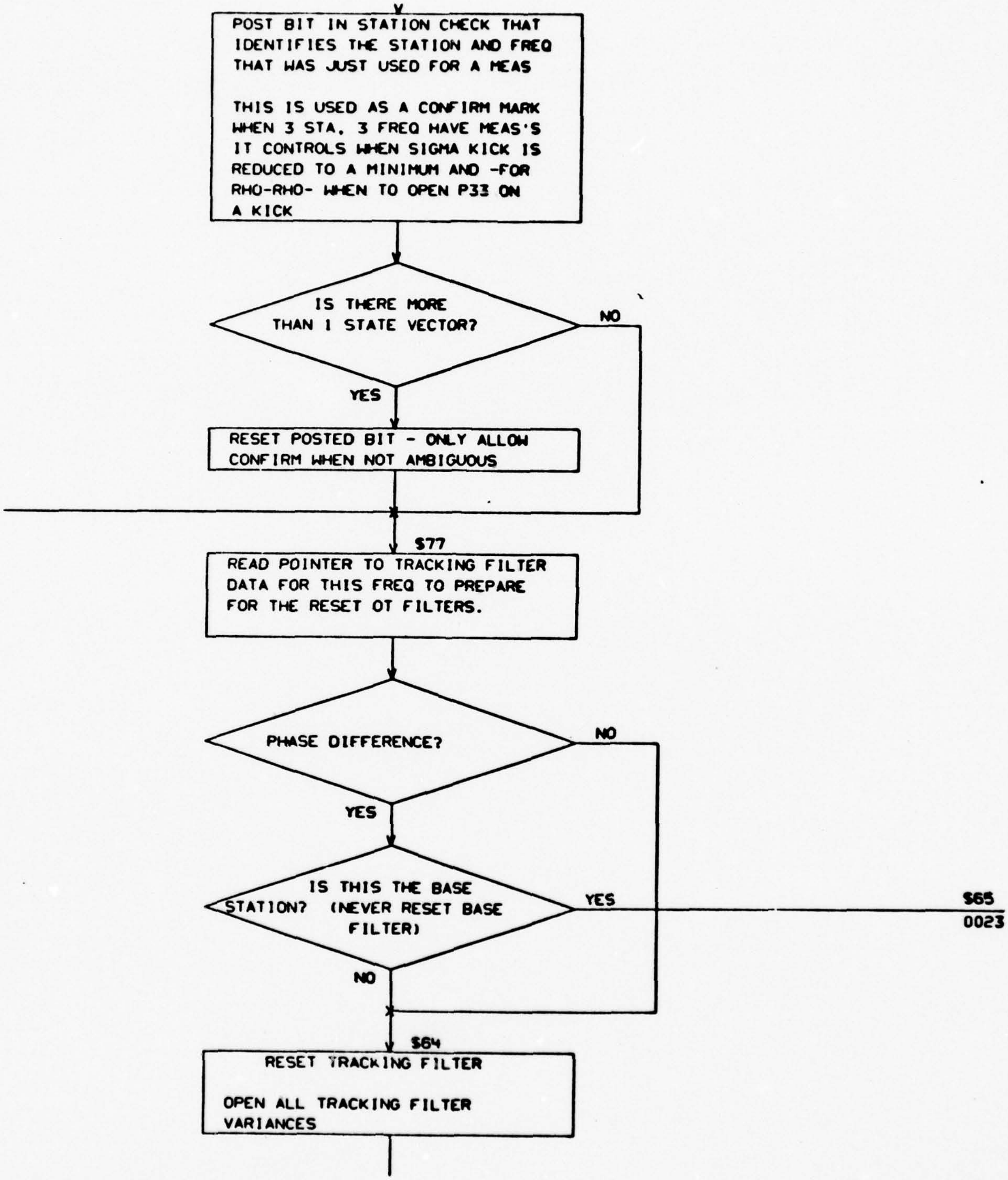

$42
GET POINTER TO SAVED POSITION MATRIX
COMPUTE AND SAVE R . S1, R . S2 AND R . S3 FOR M MATRIX
BSV
MATRIX 3D
COMPUTE PREDICTED CENTRAL ANGLE
BSV
COMPUTE THETA1
SIN THETA 1
BSV
SIN
HAS THE BASE DATA BEEN COMPUTED YET?
NO
$43
0016
YES
IS THE STATION TOO CLOSE? (360 N MILE)
NO
No
Is it too far (120°) ?
No
Yes
YES
SET N COUNTER AND NUMBER OF KALMAN DUMPS = 0 FOR ALL 3 FREQ
K EXIT
0025
$9
COMPUTE POINTERS FOR STATION AND BASE PROPAGATION DATA
• START MEASUREMENT LOOP

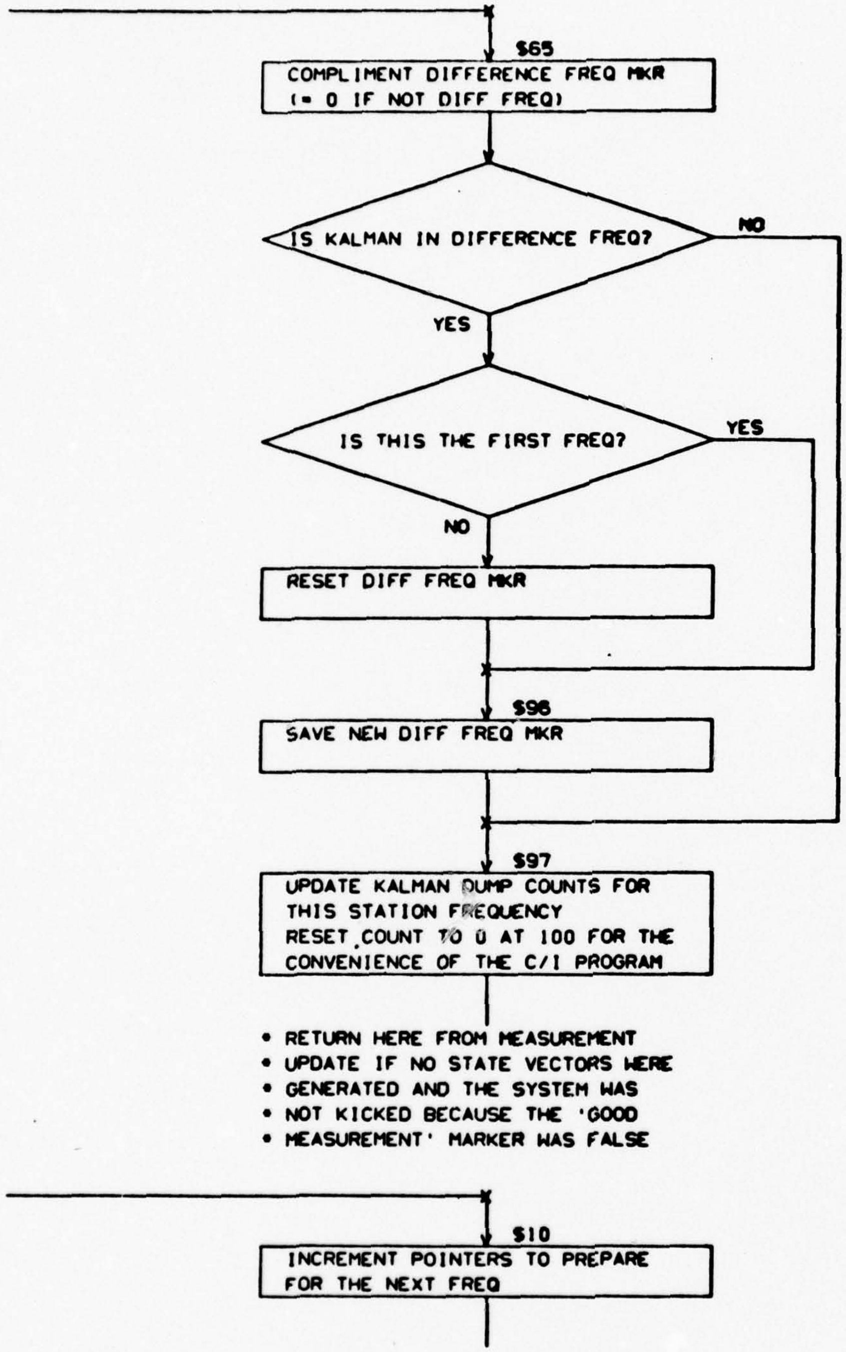

$11
SET PROGRAM FLAG D TRUE IF THIS FREQ QUALIFIES AS A GOOD MEAS
IS THERE A MEASUREMENT FROM THIS FREQ? (N = 3)
NO
$10
0023
YES
• COMPUTE M MATRIX
SET POINTER FOR BASE DATA
$46
SET M1 = M2 = 0
$45
COMPUTE M1, M2
M1 = (S.R2)*LAMBDA/SIN(THETA 1) - M1
M2 = (S.R3)*LAMBDA/SIN(THETA 1) - M2
SET POINTER FOR STATION DATA
ARE THE M'S COMPLETE?
YES
$44
0019
NO
PHASE DIFFERENCE? M(STA)- M(BASE)
YES
NO

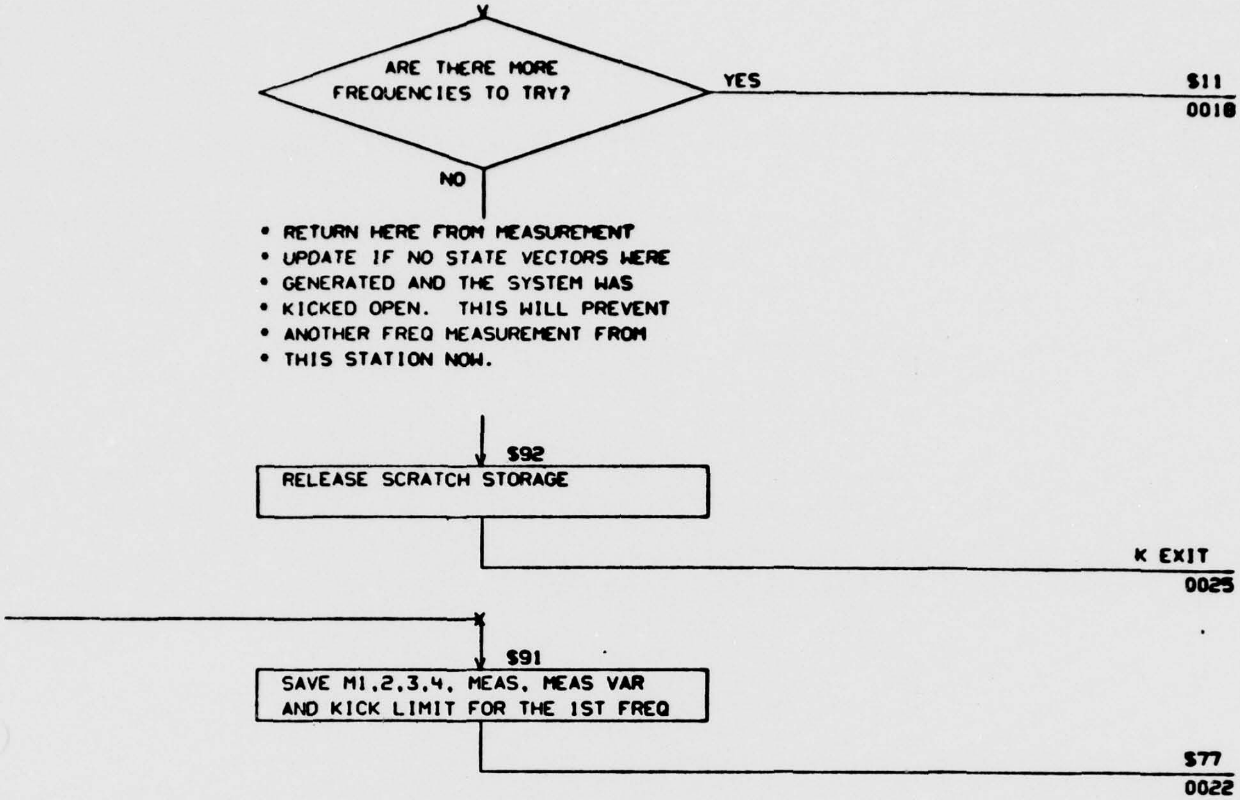

RHO-RHO DON'T NEED BASE M'S
$46
0018
$44
SET KICK LIMIT = V LAMBDA
PHASE DIFFERENCE?
YES
NO
RHO-RHO
SET M3 = V LAMBDA
$47
READ PROPAGATION VARIANCE FOR STATION
PHASE DIFFERENCE?
NO
YES
ADD PROPAGATION VARIANCE FOR BASE STATION
$49
MEASUREMENT VARIANCE = PROPAGATION VARIANCE + SIGMA SQ PHI PHI
PHASE DIFFERENCE?
NO
$50
0020
YES


IS THIS A
BASE STATION MEASUREMENT?
NO
YES
READ M4 FROM A TABLE
NOTE - M1, M2 WILL BE ZERO
USE PHI DOT DR FROM THE TRACKING
FILTER AS THE 'PREDICTED'
MEASUREMENT REFERENCE
$51
0021
$50
GET STATION NO., FREQ AND
THETA 1 ARGUMENTS FOR THETA C
COMPUTE PREDICTED TOTAL PHASE
FOR THE STATION
BSV
THETA C
PHASE DIFFERENCE?
NO
$51
0021
YES
GET BASE STATION NO., FREQ AND
THETA 1 ARGUMENTS FOR THETA C
COMPUTE PREDICTED TOTAL PHASE
FOR THE BASE STATION
BSV
THETA C
FORM PREDICTED PHASE DIFFERENCE


$51
COMPUTE KALMAN MEASUREMENT
= TRACKING FILTER PHI -
PREDICTED
COMPUTE DIVERGENCE CONTROL E1,2
= K * MEAS VAR / (LAMBDA)**2
E3 = K * MEASVAR/(V LAMBDA)**2
IS KALMAN IN DIFFERENCE FREQ?
NO
YES
IS THIS THE 1ST FREQ?
YES
$91
0024
NO
SECOND FREQ
FORM DIFFERENCES
M = M(2ND) - M(1ST), M1,2,3,4
KICK LIMIT = (2ND) - (1ST)
MEAS VAR = (2ND) + (1ST)
MEASUREMENT = (2ND) - (1ST)
$90
START MEASUREMENT PROCESSING
BSV
COMPUTE BI AND C
COMPLETE MEASUREMENT
BSV
MEASUREMENT UPDATE X
* MEASUREMENT UPDATE X ROUTINE
* RETURNS HERE ONLY IF A STATE
* VECTOR WAS UPDATED.
* IF NO STATE VECTORS WERE GEN-
* ERATED THEN IT RETURNS TO $10 P.0023
* IF 'GOOD MEASUREMENT' IS FALSE
* TO TRY ANOTHER FREQ. OTHERWISE
* IT RETURNS TO $92 AND EXITS
* KALMAN


POST BIT IN STATION CHECK THAT IDENTIFIES THE STATION AND FREQ THAT WAS JUST USED FOR A MEAS
THIS IS USED AS A CONFIRM MARK WHEN 3 STA, 3 FREQ HAVE MEAS'S IT CONTROLS WHEN SIGMA KICK IS REDUCED TO A MINIMUM AND -FOR RHO-RHO- WHEN TO OPEN P33 ON A KICK
IS THERE MORE THAN 1 STATE VECTOR?
NO
YES
RESET POSTED BIT - ONLY ALLOW CONFIRM WHEN NOT AMBIGUOUS
$77
READ POINTER TO TRACKING FILTER DATA FOR THIS FREQ TO PREPARE FOR THE RESET OT FILTERS.
PHASE DIFFERENCE?
NO
YES
IS THIS THE BASE STATION? (NEVER RESET BASE FILTER)
YES
$65
0023
NO
$64
RESET TRACKING FILTER
OPEN ALL TRACKING FILTER VARIANCES


$65
COMPLIMENT DIFFERENCE FREQ MKR
(= 0 IF NOT DIFF FREQ)
IS KALMAN IN DIFFERENCE FREQ?
NO
YES
IS THIS THE FIRST FREQ?
YES
NO
RESET DIFF FREQ MKR
$96
SAVE NEW DIFF FREQ MKR
$97
UPDATE KALMAN DUMP COUNTS FOR
THIS STATION FREQUENCY
RESET COUNT TO 0 AT 100 FOR THE
CONVENIENCE OF THE C/I PROGRAM
• RETURN HERE FROM MEASUREMENT
• UPDATE IF NO STATE VECTORS WERE
• GENERATED AND THE SYSTEM WAS
• NOT KICKED BECAUSE THE 'GOOD
• MEASUREMENT' MARKER WAS FALSE
$10
INCREMENT POINTERS TO PREPARE
FOR THE NEXT FREQ


ARE THERE MORE FREQUENCIES TO TRY?
YES
$11
0018
NO
• RETURN HERE FROM MEASUREMENT
• UPDATE IF NO STATE VECTORS WERE
• GENERATED AND THE SYSTEM WAS
• KICKED OPEN. THIS WILL PREVENT
• ANOTHER FREQ MEASUREMENT FROM
• THIS STATION NOW.
$92
RELEASE SCRATCH STORAGE
K EXIT
0025
$91
SAVE M1,2,3,4, MEAS, MEAS VAR AND KICK LIMIT FOR THE 1ST FREQ
$77
0022

- KALMAN COMPLETE
- LOOK FOR CONFIRM AND EXECUTE
- PROPAGATION PREDICTION

K EXIT

SET NO KICK MARKER TRUE IF THE STATION CHECK WORD SHOWS THAT THERE HAVE BEEN MEASUREMENTS FROM 3 FREQ ON 3 STATIONS SINCE THE SYSTEM WAS LAST IN DIFF FREQ OR HAD MORE THAN 1 STATE VECTOR

RESET KALMAN IN PROCESS MARKER

INCREMENT A COUNTER TO CYCLE ALL STATIONS THROUGH PROP PREDICTION (ONE EVERY 10 SECONDS)

COMPUTE THETA1, THETA2 AND PROP C FOR 1 STATION

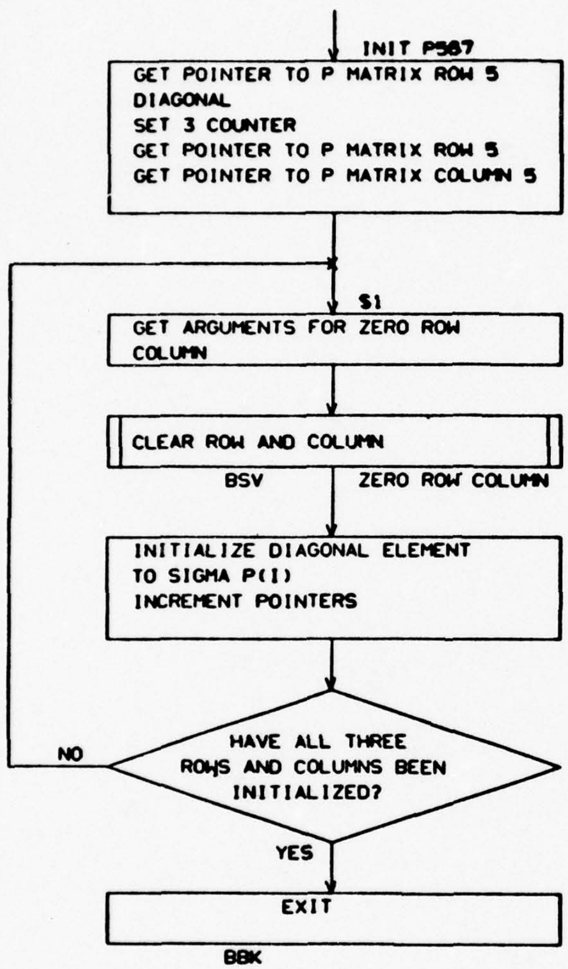
BSV

PROPAGATION PREDICTI
ON

RELEASE PROP SCRATCH STORAGE

BBK

* INITIALIZE P5, P6, P7
*
* THIS ROUTINE WILL INITIALIZE THE 5TH, 6TH AND 7TH ROWS AND COLUMNS
* OF THE P MATRIX
*



```
*                    PHI (P) PHI TRANSPOSE
*
* THIS ROUTINE MULTIPLIES PHI BY (X), (P), OR (P)TRANSPOSE.  THE RESULT
* REPLACES THE ORIGINAL MULTIPLIER.  THE 14 PHI ELEMENTS CONSIST OF
* 0, 0, PHI(1,8), 0, 0, 0, 0, PHI(2,9), PHI(3,4), PHI(5,5), PHI(6,6),
* PHI(7,7), PHI(8,8) AND PHI(9,9).  THEY ARE ORDERED BY THE SEQUENCE OF
* USEAGE WHEN ACCESSING PHI COLUMN BY COLUMN.  THE UNITY TERM OF THE
* DIAGONAL ELEMENTS DOES NOT APPEAR AS IT IS HANDLED SEPARATELY.
*
*
* ENTER HERE WITH J = 18 AND I = 2
* TO MULTIPLY BY P.  ENTER HERE
* WITH J = 2 AND I = 18 TO MULTIPLY
* BY P TRANSPOSE
```

PHI P PHIT

READ POINTER TO P AND CREATE
13 REGISTERS
SET UP COUNTER K=9 TO PROCESS P

```
* ENTER HERE WITH I = 1, POINTER TO
* X, 13 REGISTERS AND COUNTER K=1
* TO PROCESS X (J IS NOT USED)
```

$6

SET UP TWO 9 COUNTERS M AND N
READ POINTER FOR TEMP VECTOR
TO SAVE INTERMIDIATE RESULTS

$5

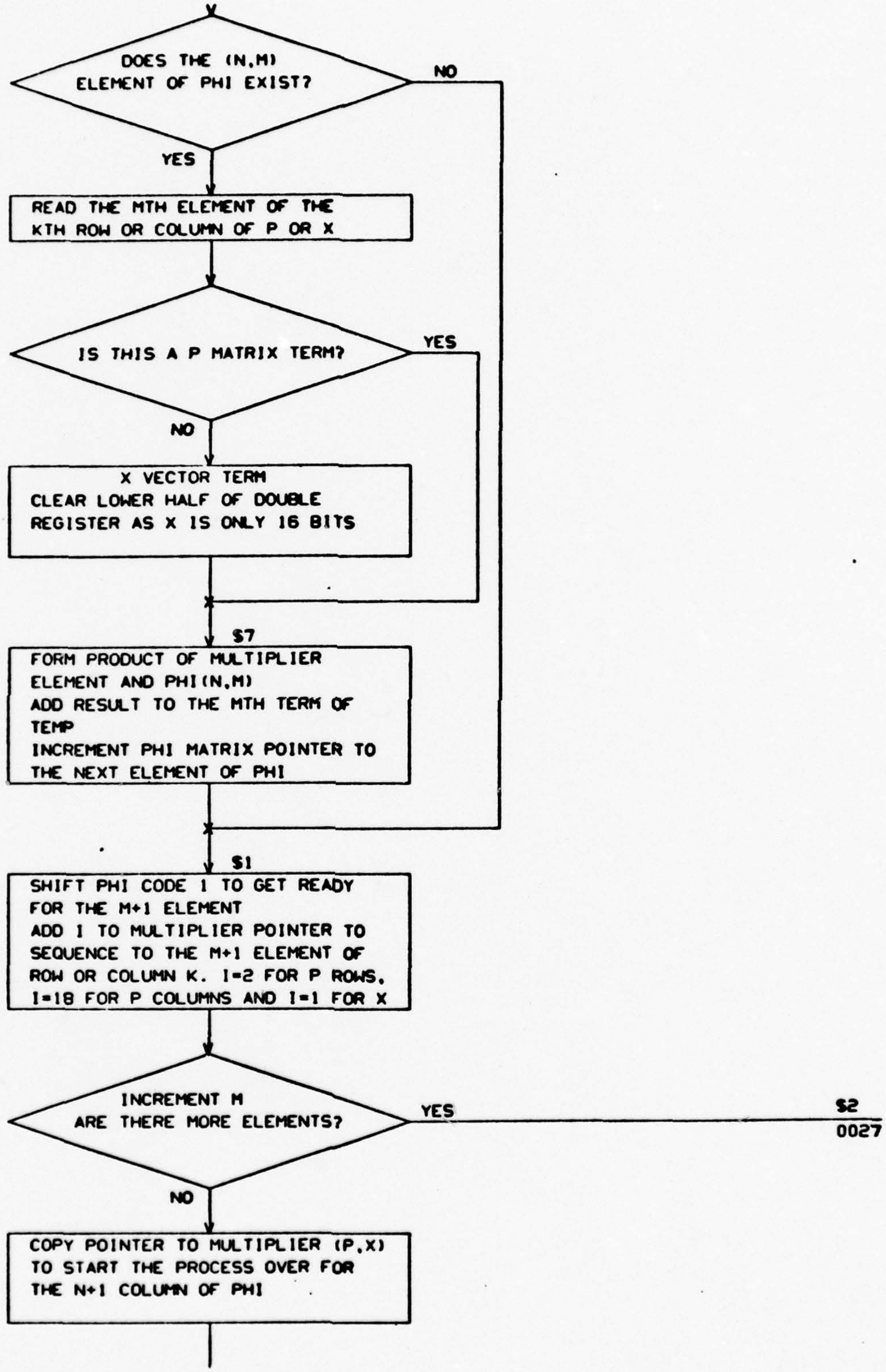
READ POINTER TO START OF PHI
MATRIX ELEMENTS
COPY POINTER TO MULTIPLIER (P,X)

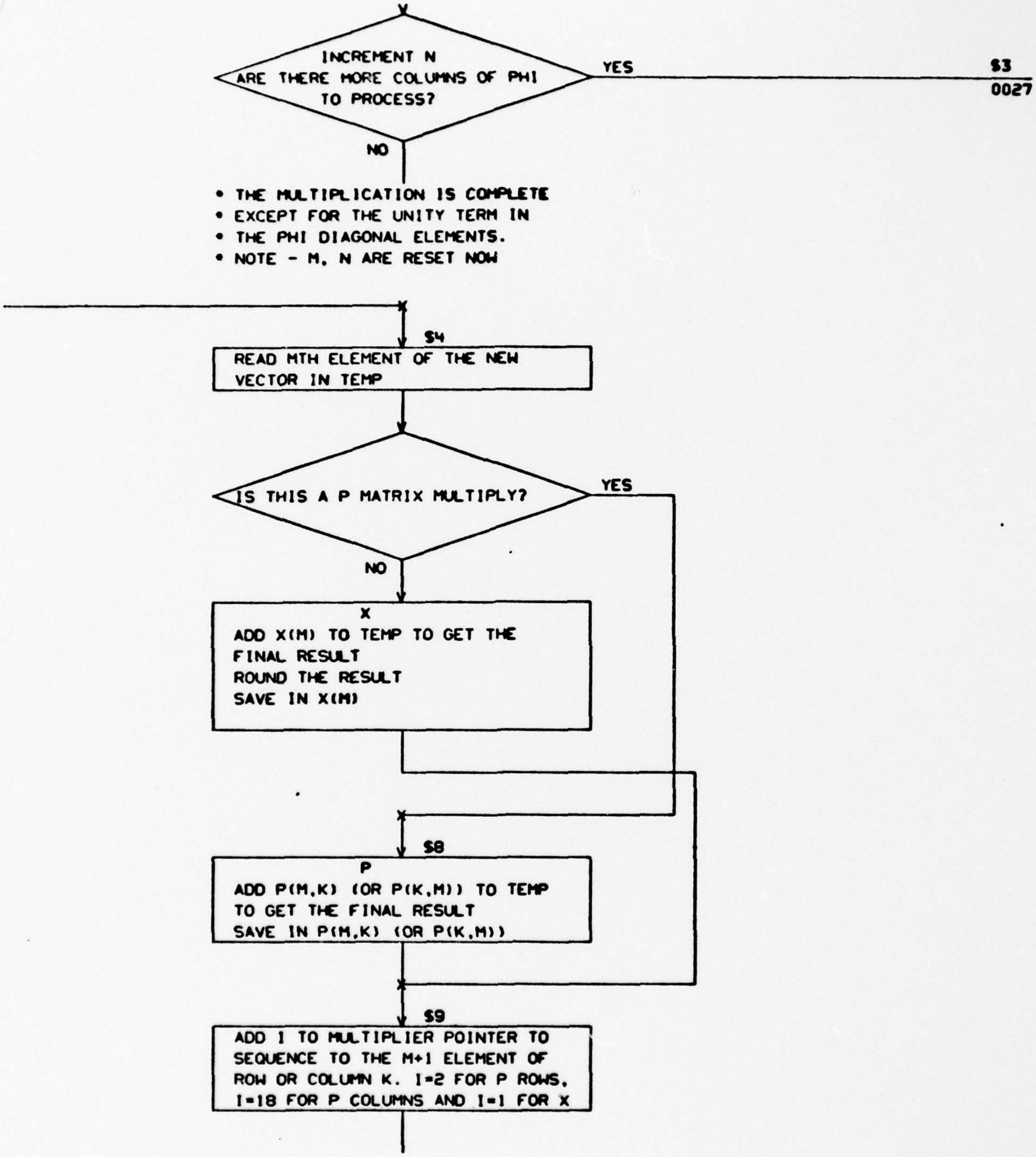
$3

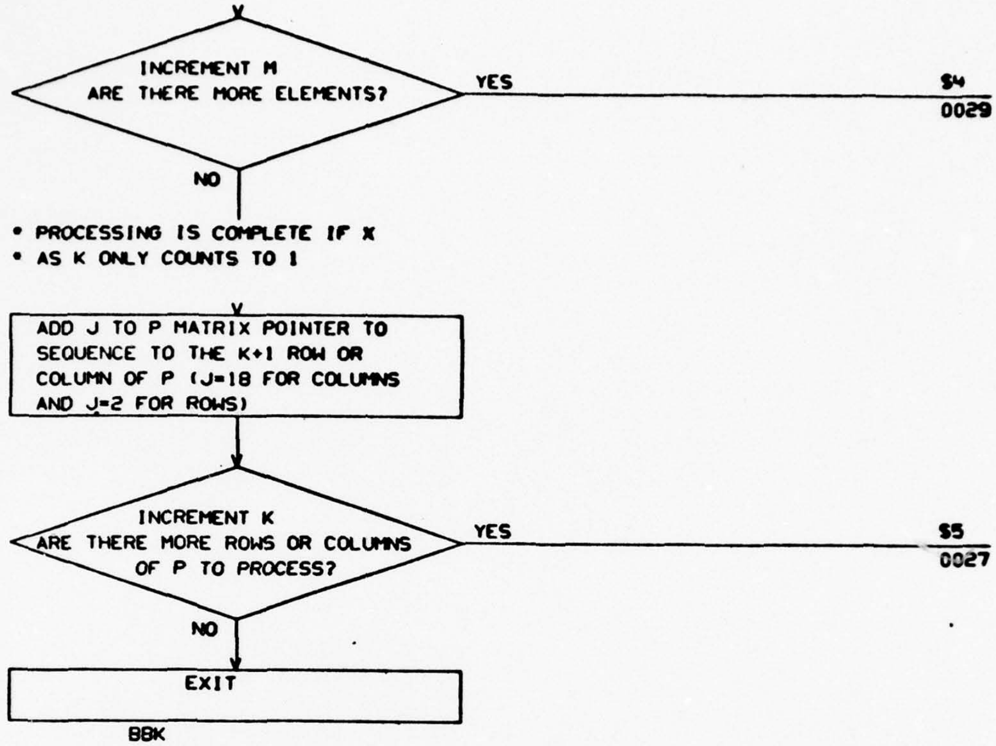
READ PHI CODE (N) FOR THIS
COLUMN
SET NTH ELEMENT OF TEMP = 0

$2

EXAMINE MSB OF PHI CODE TO DE-
TERMINE IF THIS ELEMENT OF PHI
IS ONE OF THE 14 PROVIDED FOR
IN PHI MATRIX


DOES THE (N,M) ELEMENT OF PHI EXIST?
NO
YES
READ THE MTH ELEMENT OF THE KTH ROW OR COLUMN OF P OR X
IS THIS A P MATRIX TERM?
YES
NO
X VECTOR TERM
CLEAR LOWER HALF OF DOUBLE REGISTER AS X IS ONLY 16 BITS
$7
FORM PRODUCT OF MULTIPLIER ELEMENT AND PHI(N,M)
ADD RESULT TO THE MTH TERM OF TEMP
INCREMENT PHI MATRIX POINTER TO THE NEXT ELEMENT OF PHI
$1
SHIFT PHI CODE 1 TO GET READY FOR THE M+1 ELEMENT
ADD I TO MULTIPLIER POINTER TO SEQUENCE TO THE M+1 ELEMENT OF ROW OR COLUMN K. I=2 FOR P ROWS, I=18 FOR P COLUMNS AND I=1 FOR X
INCREMENT M
ARE THERE MORE ELEMENTS?
YES
$2
0027
NO
COPY POINTER TO MULTIPLIER (P,X) TO START THE PROCESS OVER FOR THE N+1 COLUMN OF PHI


INCREMENT N
ARE THERE MORE COLUMNS OF PHI
TO PROCESS?
YES
$3
0027
NO
• THE MULTIPLICATION IS COMPLETE
• EXCEPT FOR THE UNITY TERM IN
• THE PHI DIAGONAL ELEMENTS.
• NOTE - M, N ARE RESET NOW
$4
READ MTH ELEMENT OF THE NEW
VECTOR IN TEMP
IS THIS A P MATRIX MULTIPLY?
YES
NO
X
ADD X(M) TO TEMP TO GET THE
FINAL RESULT
ROUND THE RESULT
SAVE IN X(M)
$8
P
ADD P(M,K) (OR P(K,M)) TO TEMP
TO GET THE FINAL RESULT
SAVE IN P(M,K) (OR P(K,M))
$9
ADD I TO MULTIPLIER POINTER TO
SEQUENCE TO THE M+1 ELEMENT OF
ROW OR COLUMN K. I=2 FOR P ROWS,
I=18 FOR P COLUMNS AND I=1 FOR X


INCREMENT M
ARE THERE MORE ELEMENTS?
YES
$4
0029
NO
• PROCESSING IS COMPLETE IF X
• AS K ONLY COUNTS TO 1
ADD J TO P MATRIX POINTER TO SEQUENCE TO THE K+1 ROW OR COLUMN OF P (J=18 FOR COLUMNS AND J=2 FOR ROWS)
INCREMENT K
ARE THERE MORE ROWS OR COLUMNS OF P TO PROCESS?
YES
$5
0027
NO
EXIT
BBK

```
*                        P SYM
*
* THIS ROUTINE WILL FORCE THE P MATRIX TO BE SYMETRIC AND THE DIAGONAL
* ELEMENTS TO BE POSITIVE
*

                      P SYM
 SET P(M,N) = P(N,M) FOR
                M UNEQUAL N
 SET P(M,N) = 0 IF N = M
            AND P(M,N) MINUS
          BBK
```

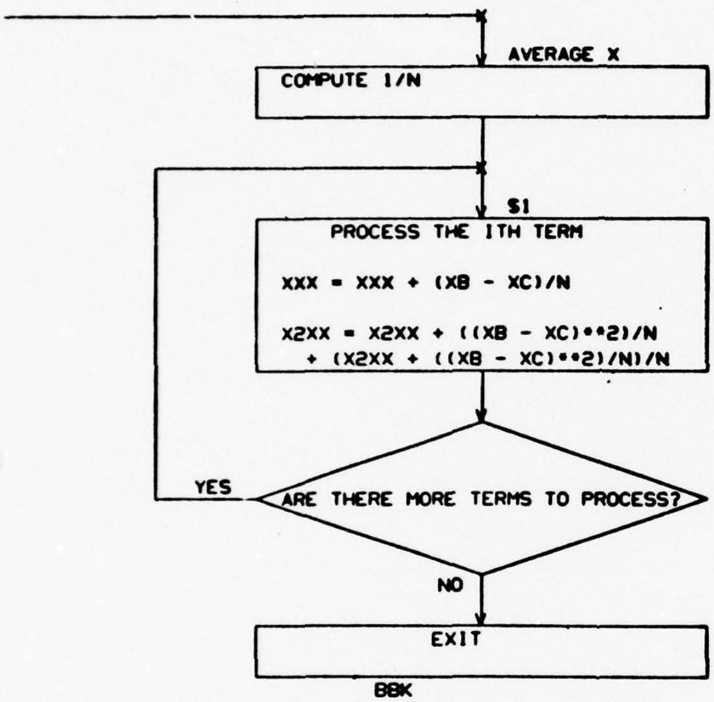
```
*                         ASSEMBLE STATE VECTOR
*
* THIS ROUTINE WILL BUILD A SINGLE 9 ELEMENT STATE VECTOR (XX) FROM ONE
* OF THE 4 ELEMENT MULTIPLE VECTORS AND THE 5 ELEMENT COMMON VECTOR
* (XXXX).  THE ARGUMENT IS A POINTER TO THE MULTIPLE VECTOR.
*
```

ASSEMBLE XX

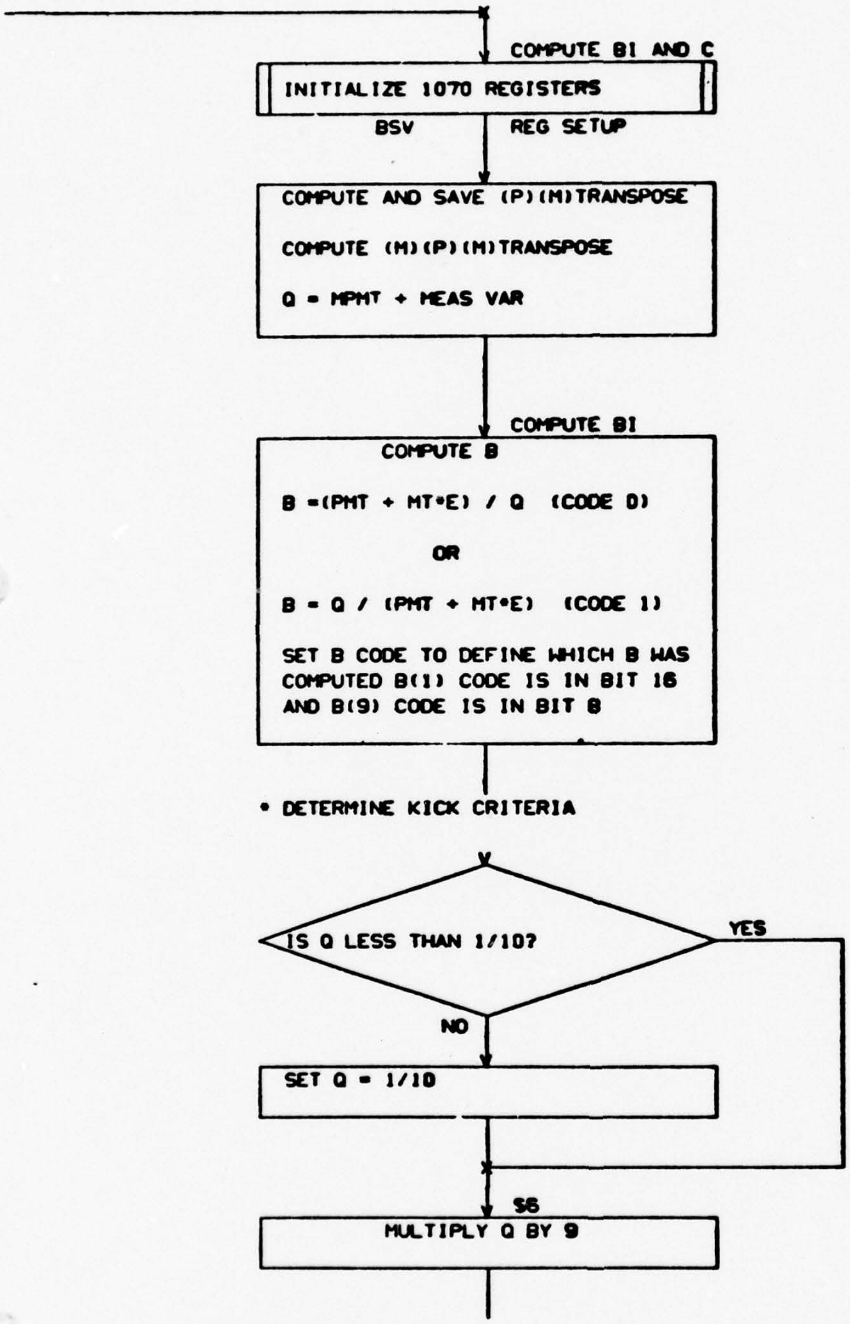
READ 5 COMMON ELEMENTS
READ 4 UNIQUE ELEMENTS
SAVE NEW 9 ELEMENT VECTOR

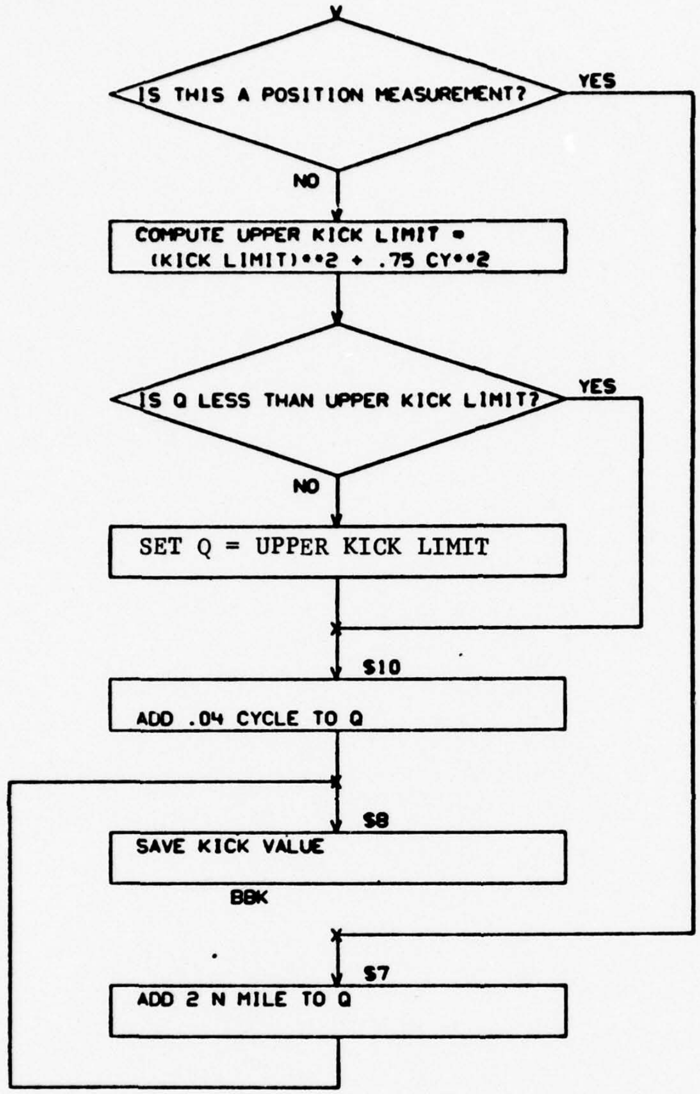
BBK

```
*                        AVERAGE X
*
* THIS ROUTINE WILL COMPUTE AN AVERAGE STATE VECTOR.  EACH TIME THIS
* ROUTINE IS CALLED IT WILL UPDATE THE AVERAGE WITH ONE STATE VECTOR.
* IT ALSO GENERATES THE VARIANCE OF EACH ELEMENT OVER THE SET OF STATE
* VECTORS.  THE ARGUMENTS CONSIST OF POINTERS TO THE NEW VECTOR (XB) AND
* THE AVERAGE VECTOR (XC)  AND THE NUMBER OF THE NEW VECTOR (N).  THE
* RESULTS ARE LEFT IN XXX (AVERAGE) AND X2XX (VARIANCE)
*
```

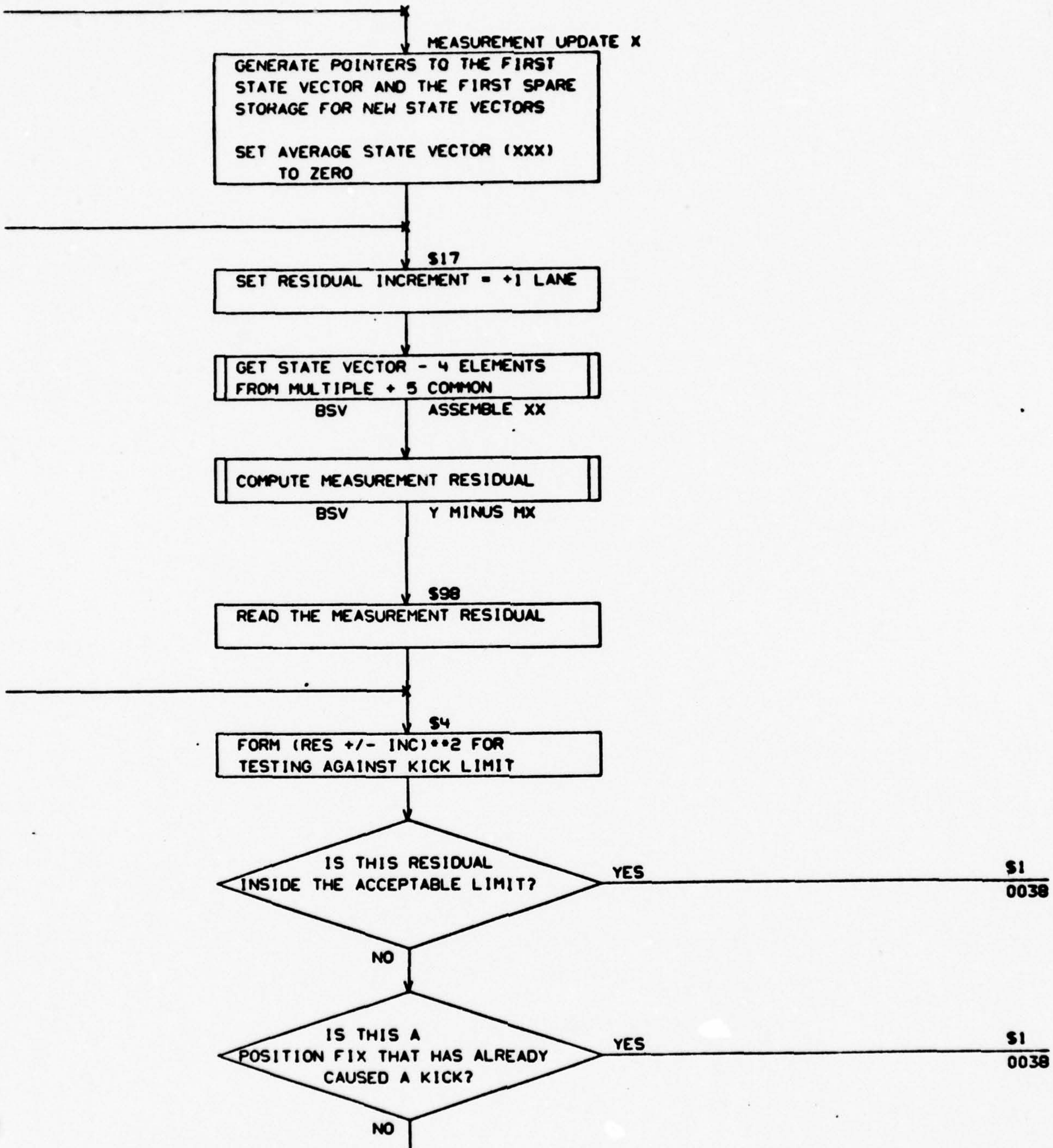


```
*                         COMPUTE BI AND C
*
* THIS ROUTINE COMPUTES THE MEASUREMENT WEIGHTING VECTOR B
*
```

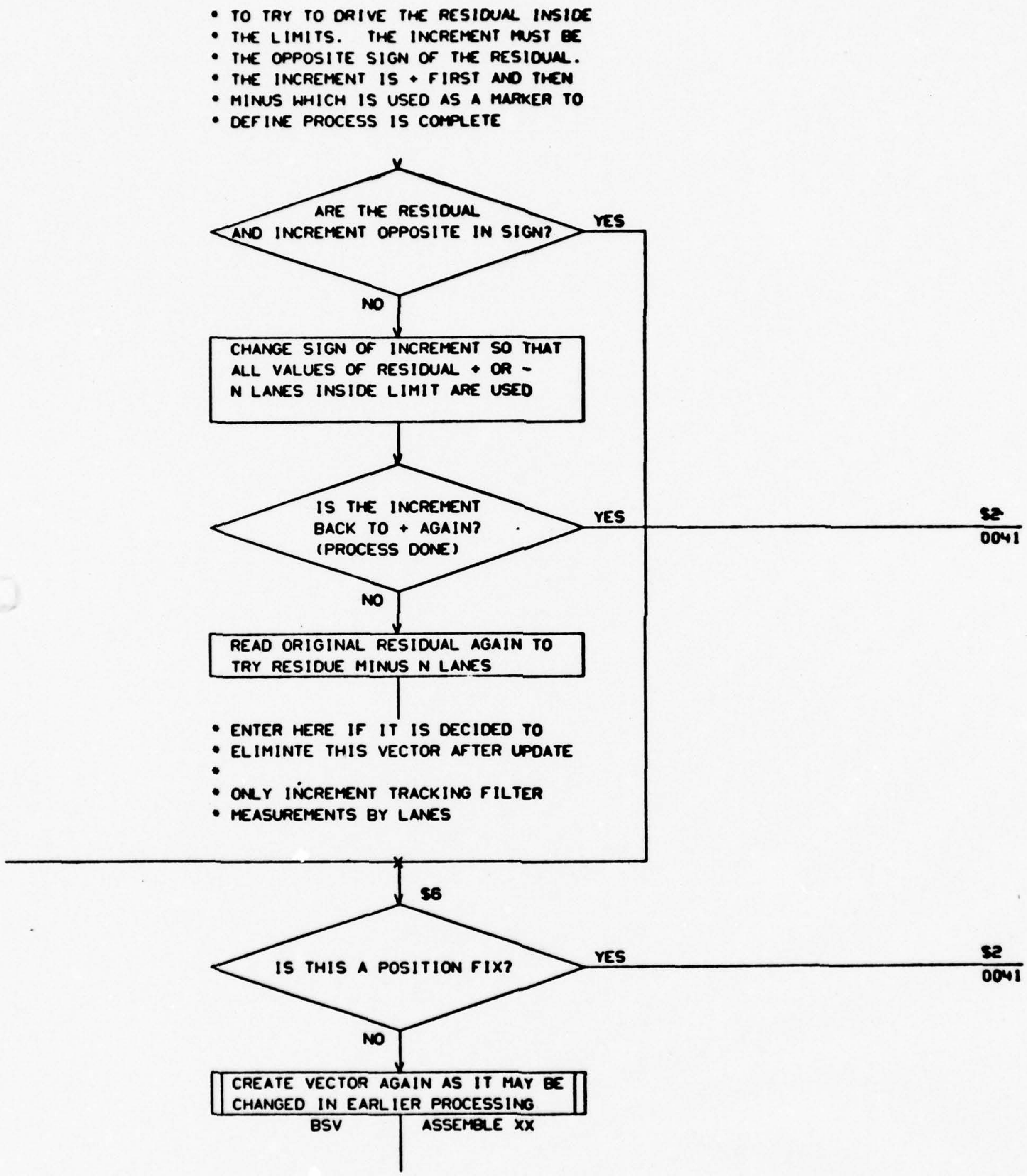


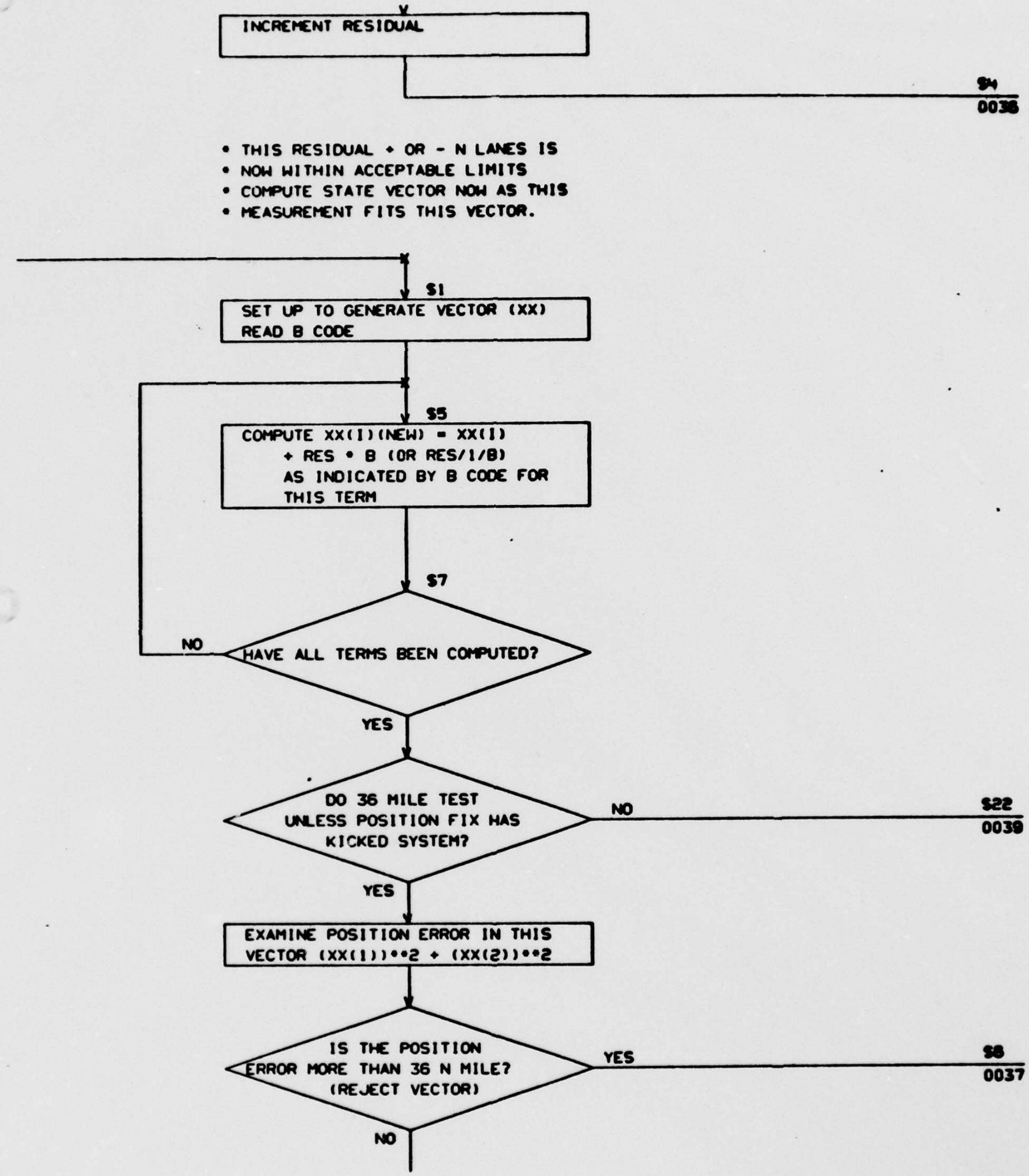

IS THIS A POSITION MEASUREMENT?
YES
NO
COMPUTE UPPER KICK LIMIT =
(KICK LIMIT)**2 + .75 CY**2
IS Q LESS THAN UPPER KICK LIMIT?
YES
NO
SET Q = UPPER KICK LIMIT
$10
ADD .04 CYCLE TO Q
$8
SAVE KICK VALUE
BBK
$7
ADD 2 N MILE TO Q

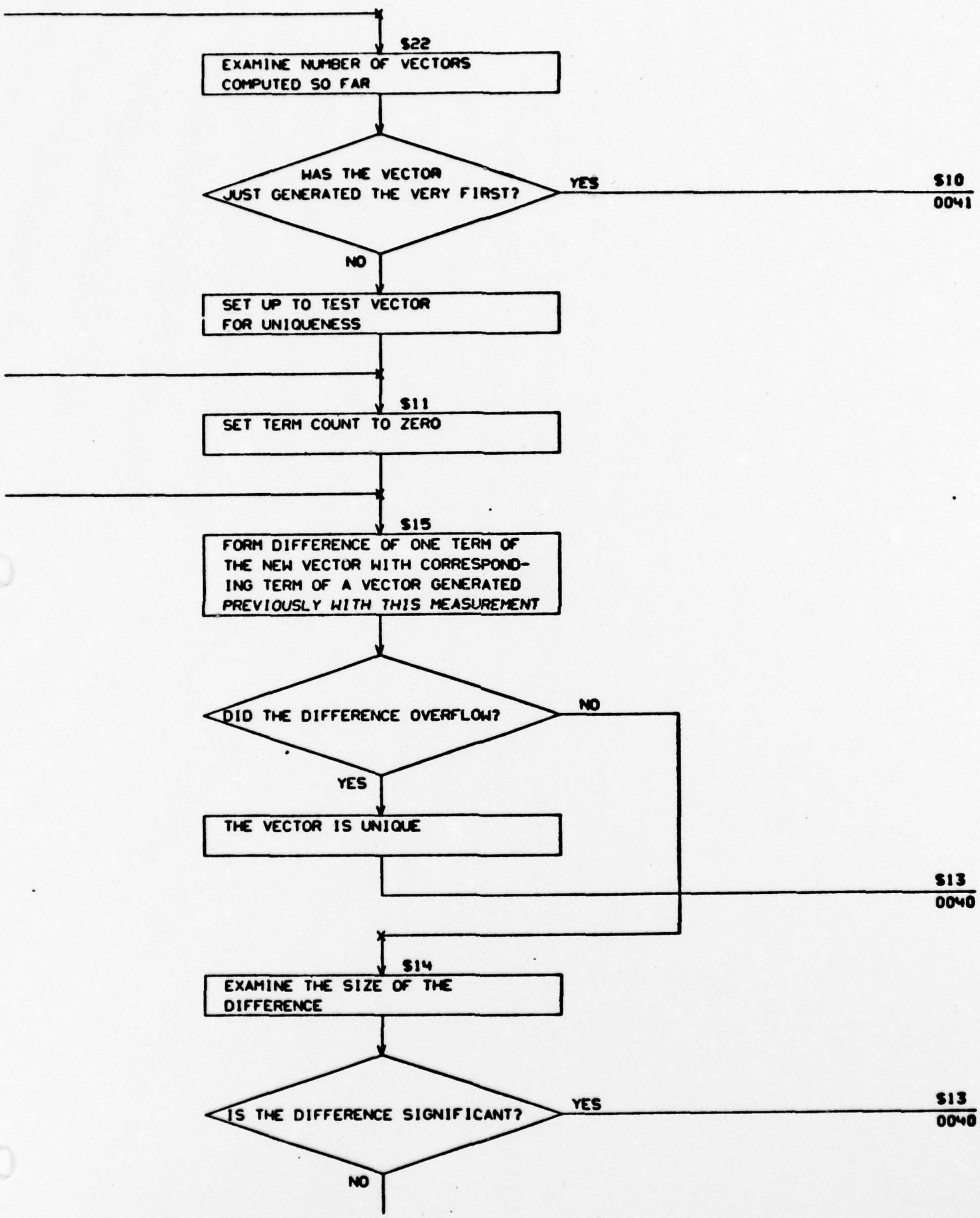
* MEASUREMENT UPDATE X
*
* UPDATE STATE VECTORS WITH THIS MEASUREMENT
*



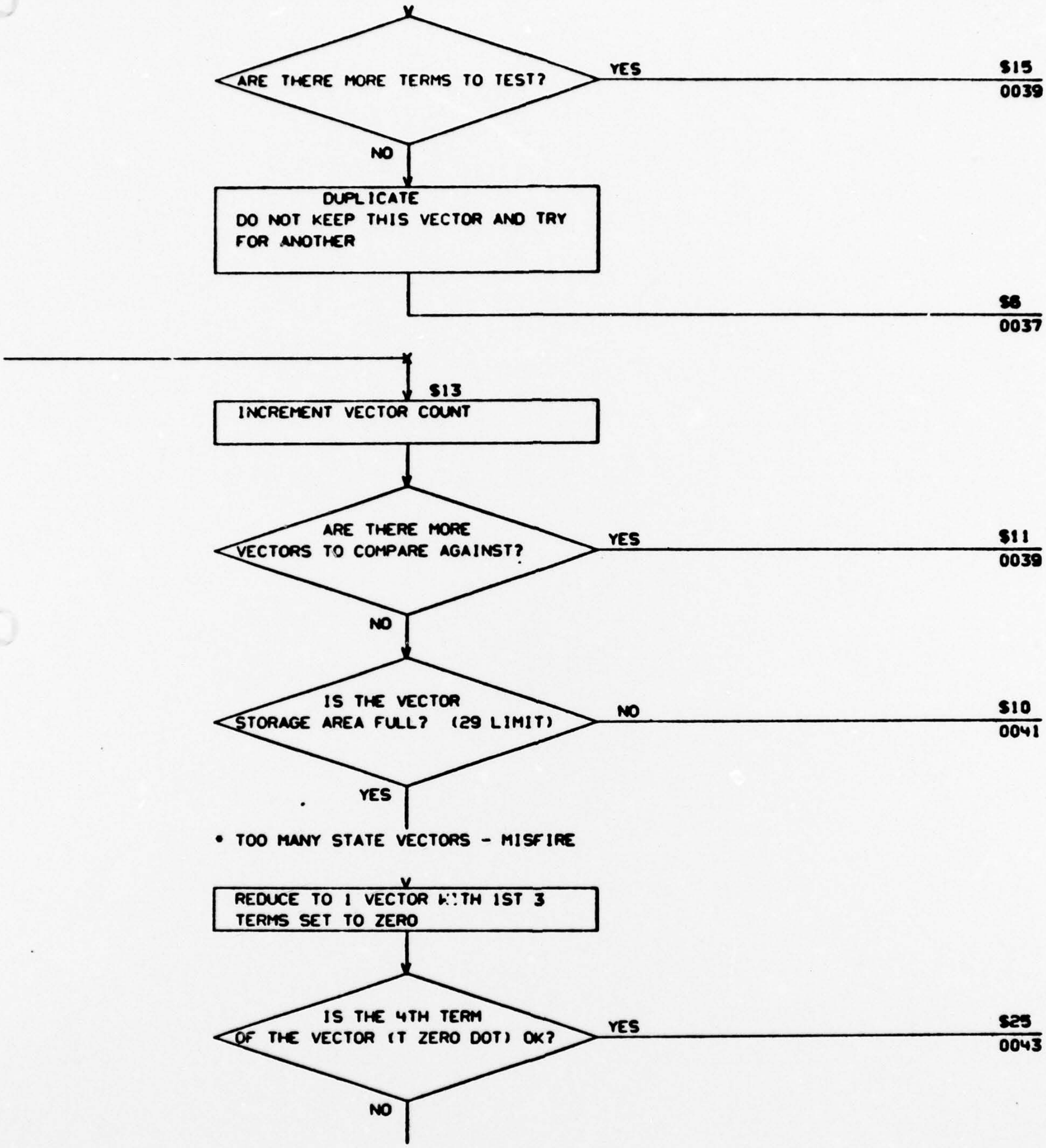
* THE RESIDUAL INCREMENT WILL BE USED

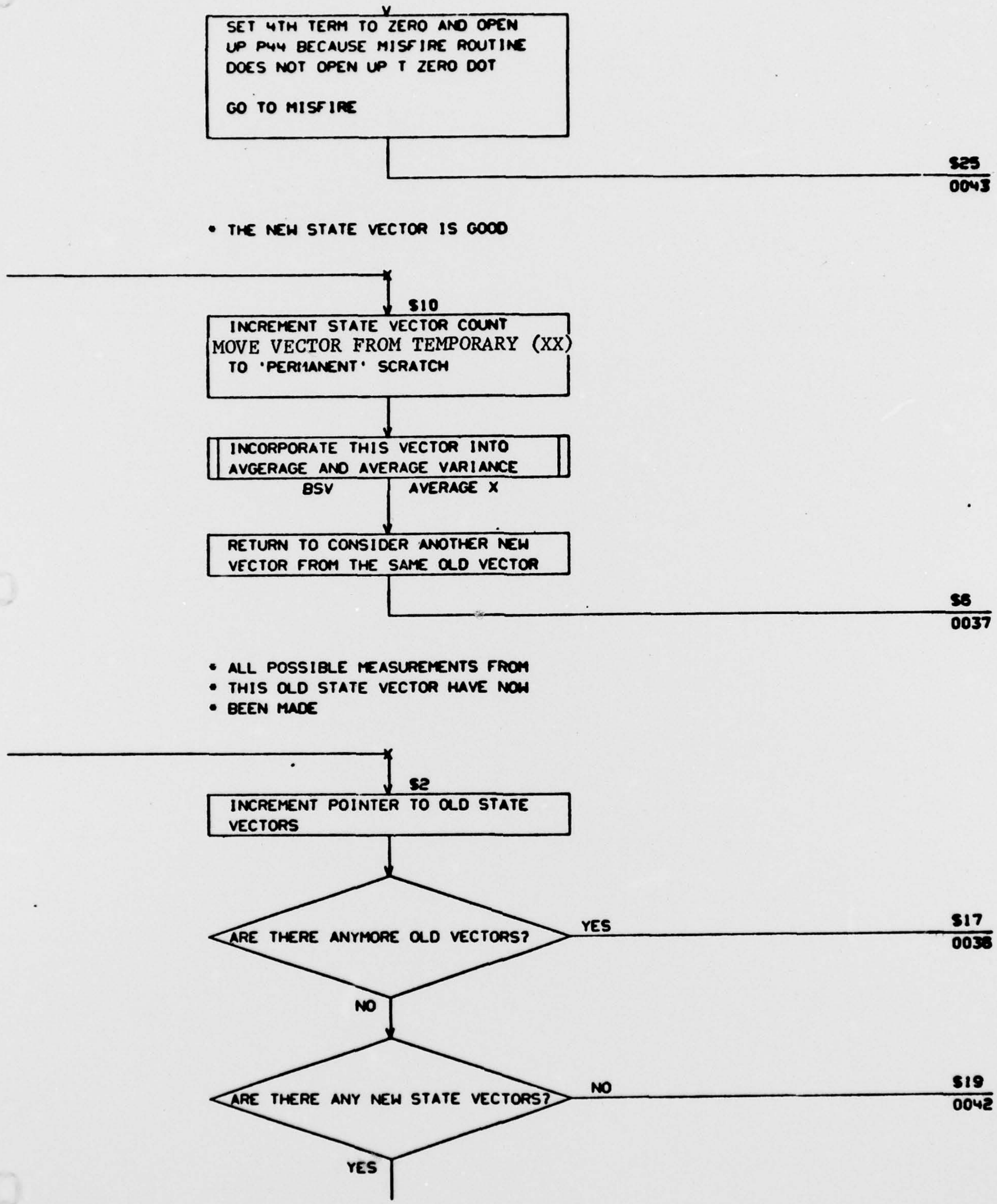

• TO TRY TO DRIVE THE RESIDUAL INSIDE
• THE LIMITS. THE INCREMENT MUST BE
• THE OPPOSITE SIGN OF THE RESIDUAL.
• THE INCREMENT IS + FIRST AND THEN
• MINUS WHICH IS USED AS A MARKER TO
• DEFINE PROCESS IS COMPLETE
ARE THE RESIDUAL AND INCREMENT OPPOSITE IN SIGN?
YES
NO
CHANGE SIGN OF INCREMENT SO THAT ALL VALUES OF RESIDUAL + OR − N LANES INSIDE LIMIT ARE USED
IS THE INCREMENT BACK TO + AGAIN? (PROCESS DONE)
YES
S2
0041
NO
READ ORIGINAL RESIDUAL AGAIN TO TRY RESIDUE MINUS N LANES
• ENTER HERE IF IT IS DECIDED TO
• ELIMINTE THIS VECTOR AFTER UPDATE
•
• ONLY INCREMENT TRACKING FILTER
• MEASUREMENTS BY LANES
S6
IS THIS A POSITION FIX?
YES
S2
0041
NO
CREATE VECTOR AGAIN AS IT MAY BE CHANGED IN EARLIER PROCESSING
BSV
ASSEMBLE XX

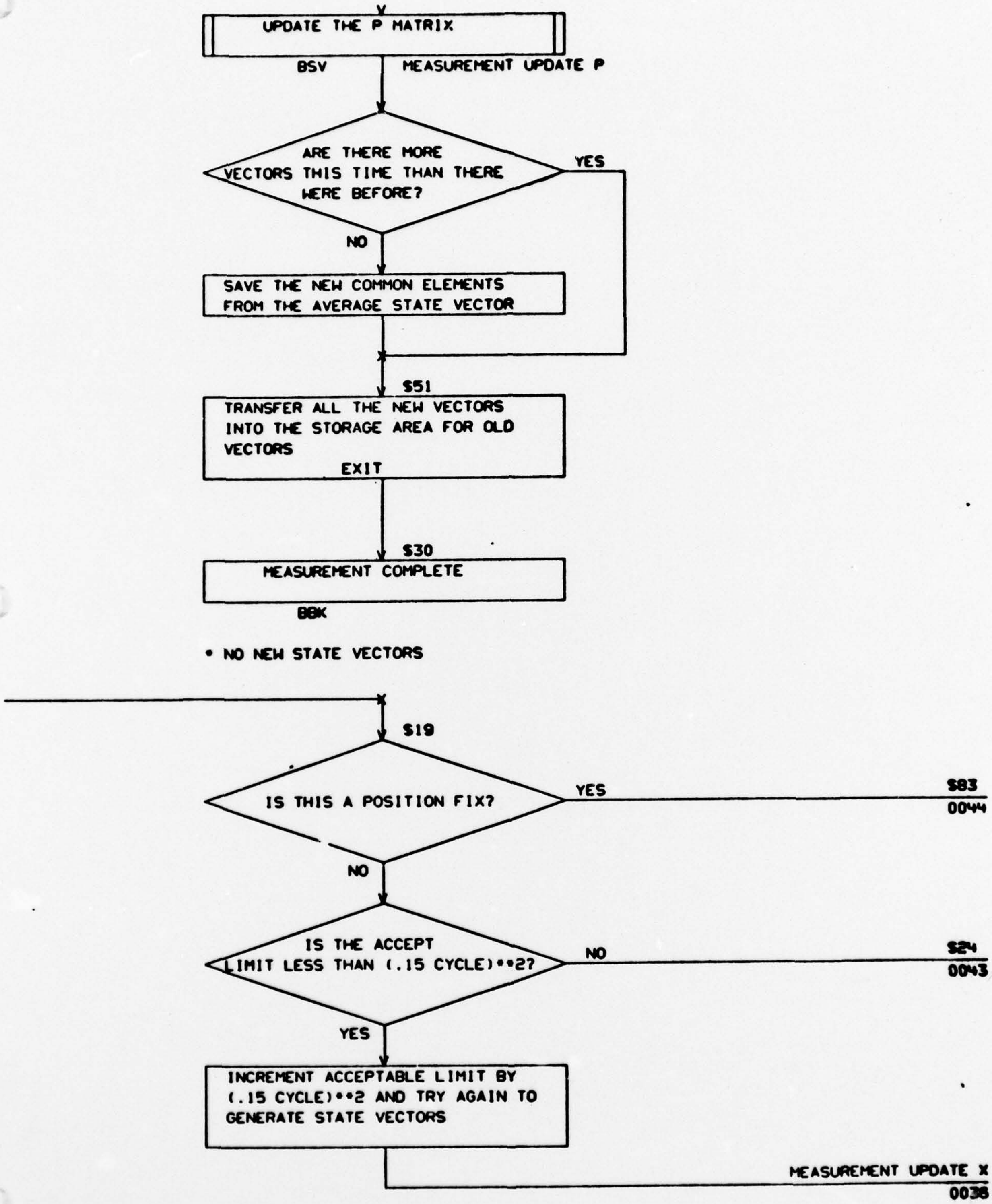

INCREMENT RESIDUAL
$4
0036
• THIS RESIDUAL + OR - N LANES IS
• NOW WITHIN ACCEPTABLE LIMITS
• COMPUTE STATE VECTOR NOW AS THIS
• MEASUREMENT FITS THIS VECTOR.
$1
SET UP TO GENERATE VECTOR (XX)
READ B CODE
$5
COMPUTE XX(I)(NEW) = XX(I)
+ RES * B (OR RES/1/B)
AS INDICATED BY B CODE FOR
THIS TERM
$7
NO
HAVE ALL TERMS BEEN COMPUTED?
YES
DO 36 MILE TEST
UNLESS POSITION FIX HAS
KICKED SYSTEM?
NO
$22
0039
YES
EXAMINE POSITION ERROR IN THIS
VECTOR (XX(1))**2 + (XX(2))**2
IS THE POSITION
ERROR MORE THAN 36 N MILE?
(REJECT VECTOR)
YES
$8
0037
NO

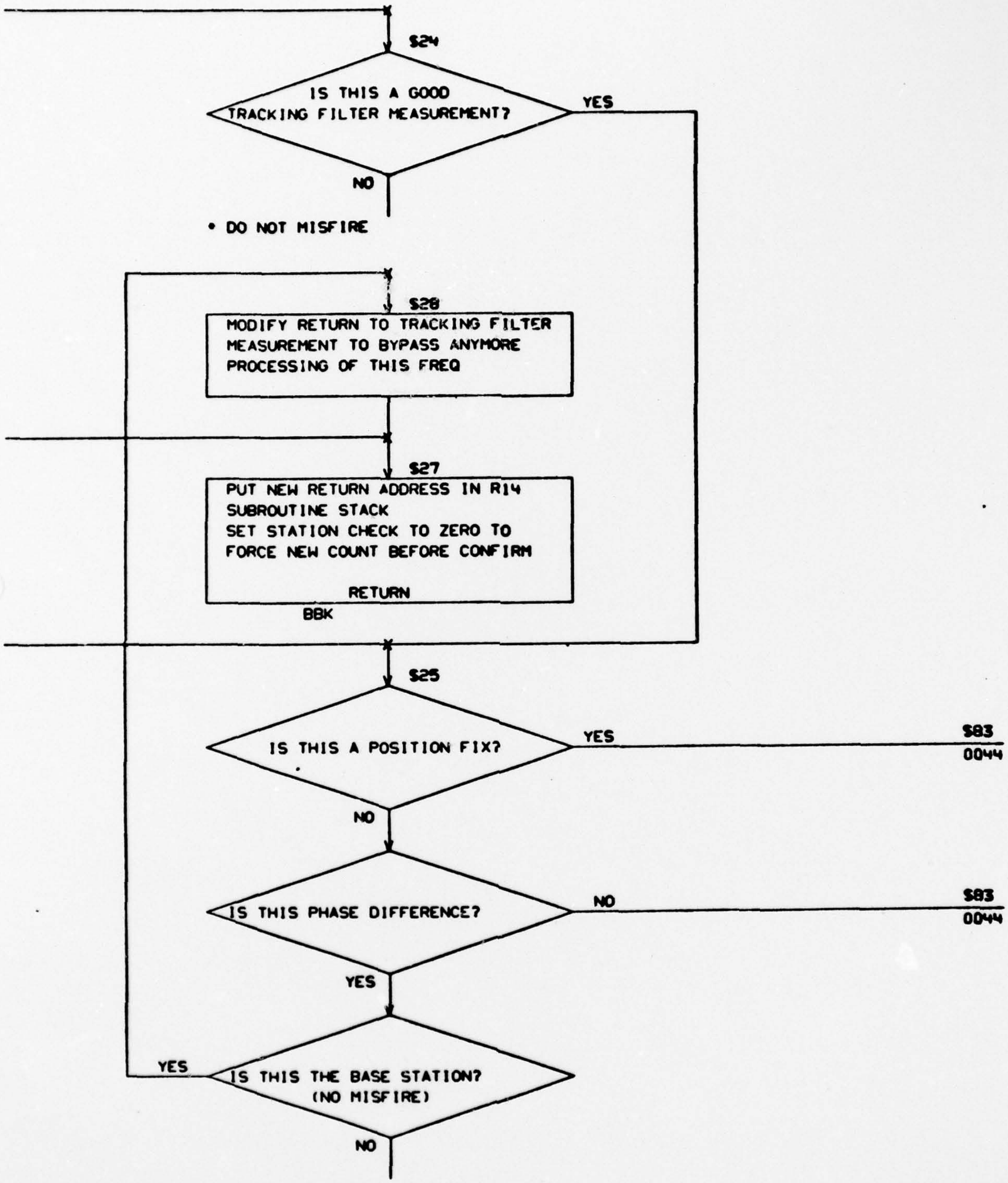


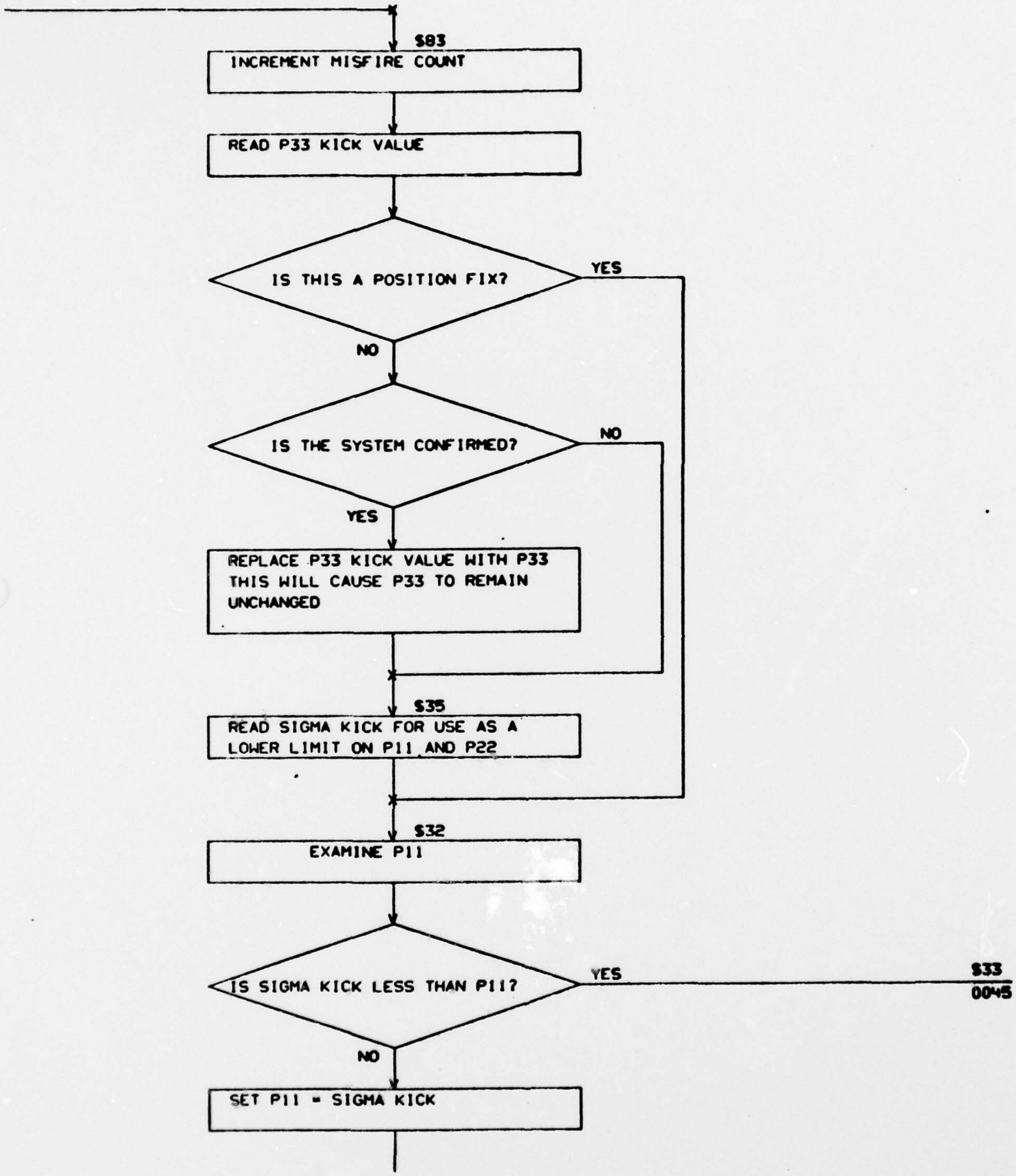
S22
EXAMINE NUMBER OF VECTORS COMPUTED SO FAR
HAS THE VECTOR JUST GENERATED THE VERY FIRST?
YES
S10
0041
NO
SET UP TO TEST VECTOR FOR UNIQUENESS
S11
SET TERM COUNT TO ZERO
S15
FORM DIFFERENCE OF ONE TERM OF THE NEW VECTOR WITH CORRESPONDING TERM OF A VECTOR GENERATED PREVIOUSLY WITH THIS MEASUREMENT
DID THE DIFFERENCE OVERFLOW?
NO
YES
THE VECTOR IS UNIQUE
S13
0040
S14
EXAMINE THE SIZE OF THE DIFFERENCE
IS THE DIFFERENCE SIGNIFICANT?
YES
S13
0040
NO

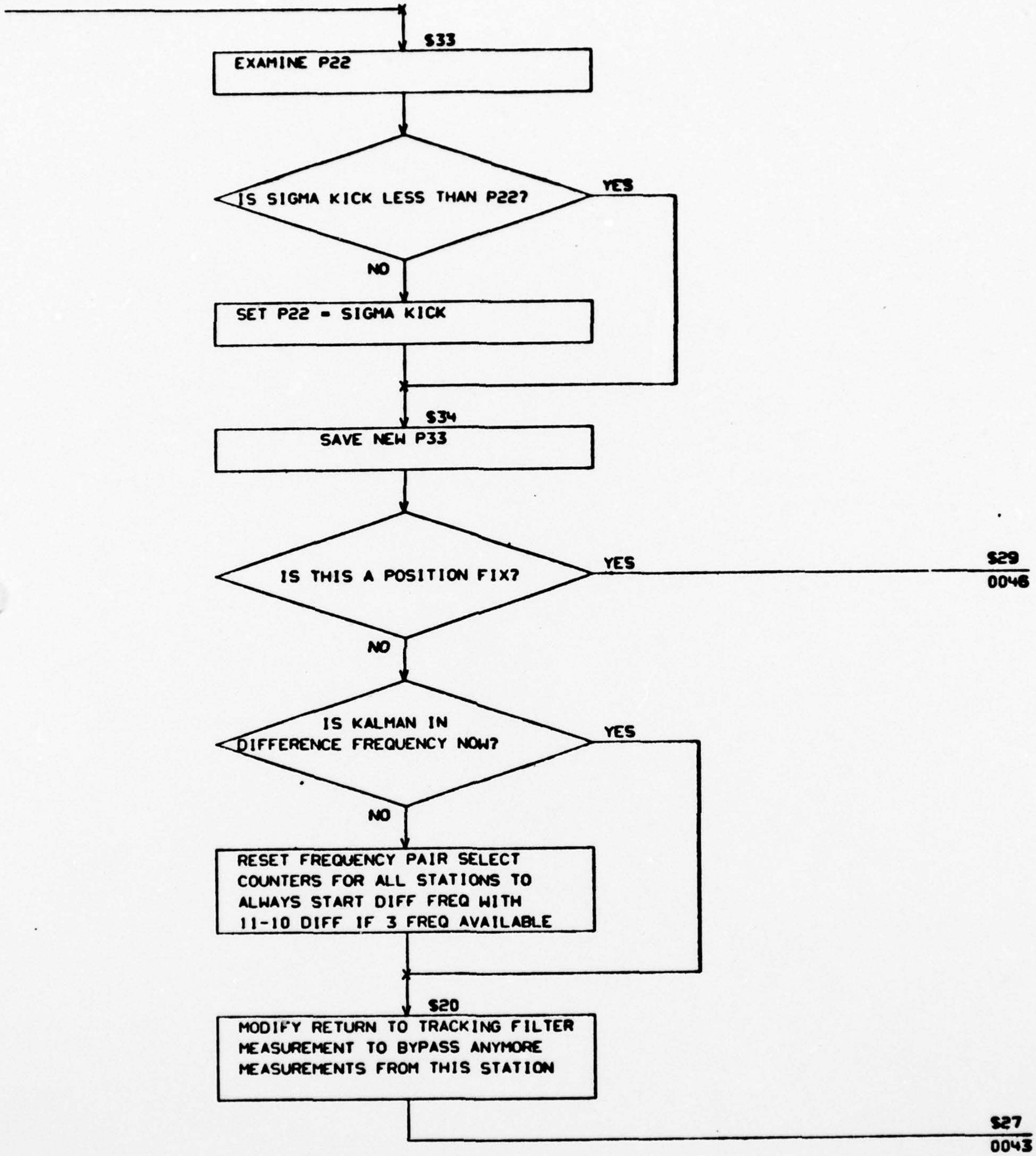

ARE THERE MORE TERMS TO TEST?
YES
$15
0039
NO
DUPLICATE
DO NOT KEEP THIS VECTOR AND TRY FOR ANOTHER
$6
0037
$13
INCREMENT VECTOR COUNT
ARE THERE MORE VECTORS TO COMPARE AGAINST?
YES
$11
0039
NO
IS THE VECTOR STORAGE AREA FULL? (29 LIMIT)
NO
$10
0041
YES
• TOO MANY STATE VECTORS - MISFIRE
REDUCE TO 1 VECTOR WITH 1ST 3 TERMS SET TO ZERO
IS THE 4TH TERM OF THE VECTOR (T ZERO DOT) OK?
YES
$25
0043
NO

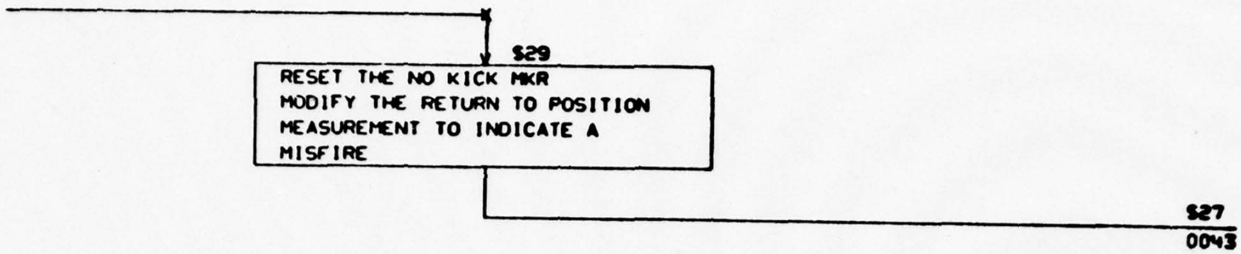

SET 4TH TERM TO ZERO AND OPEN UP P44 BECAUSE MISFIRE ROUTINE DOES NOT OPEN UP T ZERO DOT
GO TO MISFIRE
$25
0043
• THE NEW STATE VECTOR IS GOOD
$10
INCREMENT STATE VECTOR COUNT
MOVE VECTOR FROM TEMPORARY (XX) TO 'PERMANENT' SCRATCH
INCORPORATE THIS VECTOR INTO AVGERAGE AND AVERAGE VARIANCE
BSV
AVERAGE X
RETURN TO CONSIDER ANOTHER NEW VECTOR FROM THE SAME OLD VECTOR
$6
0037
• ALL POSSIBLE MEASUREMENTS FROM
• THIS OLD STATE VECTOR HAVE NOW
• BEEN MADE
$2
INCREMENT POINTER TO OLD STATE VECTORS
ARE THERE ANYMORE OLD VECTORS?
YES
$17
0038
NO
ARE THERE ANY NEW STATE VECTORS?
NO
$19
0042
YES


UPDATE THE P MATRIX
BSV
MEASUREMENT UPDATE P
ARE THERE MORE VECTORS THIS TIME THAN THERE WERE BEFORE?
YES
NO
SAVE THE NEW COMMON ELEMENTS FROM THE AVERAGE STATE VECTOR
$51
TRANSFER ALL THE NEW VECTORS INTO THE STORAGE AREA FOR OLD VECTORS
EXIT
$30
MEASUREMENT COMPLETE
BBK
• NO NEW STATE VECTORS
$19
IS THIS A POSITION FIX?
YES
$83
0044
NO
IS THE ACCEPT LIMIT LESS THAN (.15 CYCLE)**2?
NO
$24
0043
YES
INCREMENT ACCEPTABLE LIMIT BY (.15 CYCLE)**2 AND TRY AGAIN TO GENERATE STATE VECTORS
MEASUREMENT UPDATE X
0038


$24
IS THIS A GOOD TRACKING FILTER MEASUREMENT?
YES
NO
• DO NOT MISFIRE
$28
MODIFY RETURN TO TRACKING FILTER MEASUREMENT TO BYPASS ANYMORE PROCESSING OF THIS FREQ
$27
PUT NEW RETURN ADDRESS IN R14 SUBROUTINE STACK
SET STATION CHECK TO ZERO TO FORCE NEW COUNT BEFORE CONFIRM
RETURN
BBK
$25
IS THIS A POSITION FIX?
YES
$83
0044
NO
IS THIS PHASE DIFFERENCE?
NO
$83
0044
YES
YES
IS THIS THE BASE STATION? (NO MISFIRE)
NO


$83
INCREMENT MISFIRE COUNT
READ P33 KICK VALUE
IS THIS A POSITION FIX?
YES
NO
IS THE SYSTEM CONFIRMED?
NO
YES
REPLACE P33 KICK VALUE WITH P33 THIS WILL CAUSE P33 TO REMAIN UNCHANGED
$35
READ SIGMA KICK FOR USE AS A LOWER LIMIT ON P11 AND P22
$32
EXAMINE P11
IS SIGMA KICK LESS THAN P11?
YES
$33
0045
NO
SET P11 = SIGMA KICK


$33
EXAMINE P22
IS SIGMA KICK LESS THAN P22?
YES
NO
SET P22 = SIGMA KICK
$34
SAVE NEW P33
IS THIS A POSITION FIX?
YES
$29
0046
NO
IS KALMAN IN DIFFERENCE FREQUENCY NOW?
YES
NO
RESET FREQUENCY PAIR SELECT COUNTERS FOR ALL STATIONS TO ALWAYS START DIFF FREQ WITH 11-10 DIFF IF 3 FREQ AVAILABLE
$20
MODIFY RETURN TO TRACKING FILTER MEASUREMENT TO BYPASS ANYMORE MEASUREMENTS FROM THIS STATION
$27
0043


S29
RESET THE NO KICK MKR
MODIFY THE RETURN TO POSITION
MEASUREMENT TO INDICATE A
MISFIRE
S27
0043

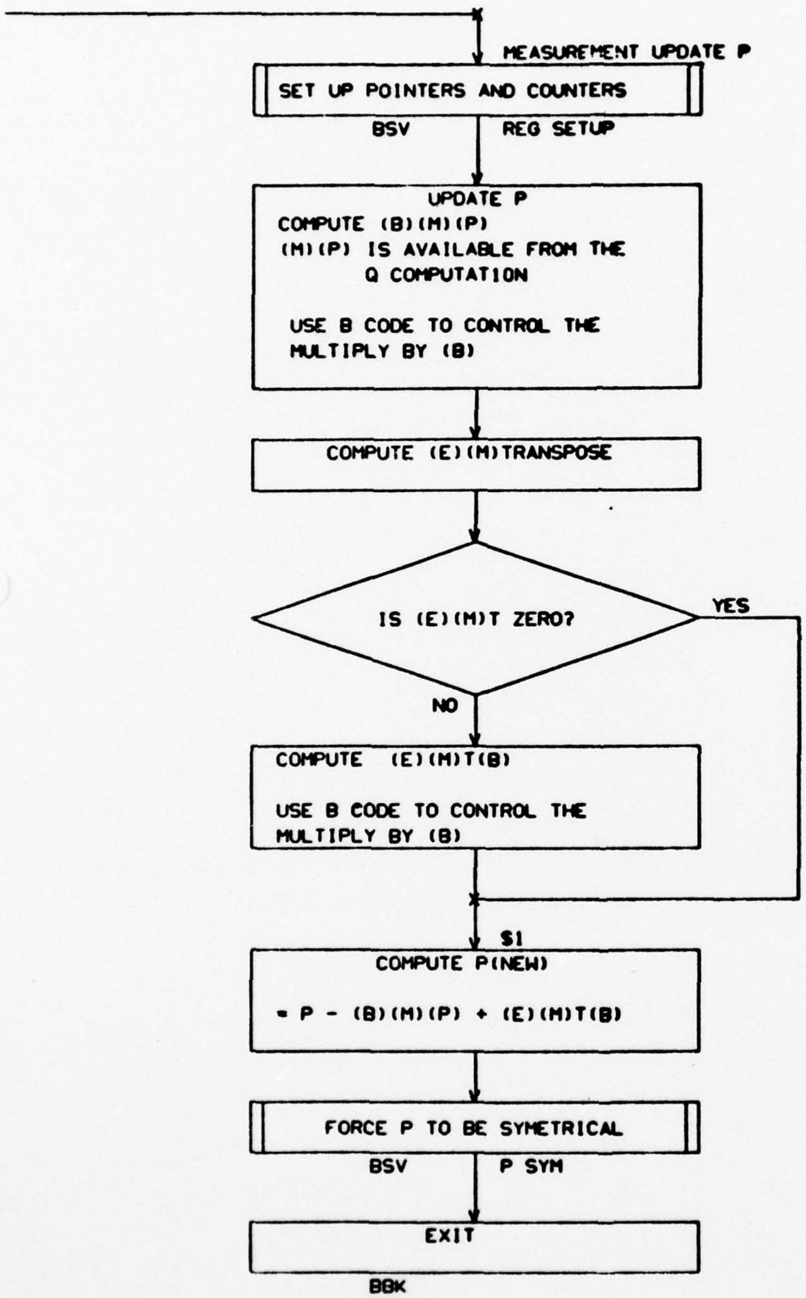
```
*                    MEASUREMENT RESIDUE
*
* THIS ROUTINE COMPUTES THE RESIDUE Y - (M)(X).  THE ARGUMENT CONSISTS
* OF A POINTER TO X.
*
```

Y MINUS MX

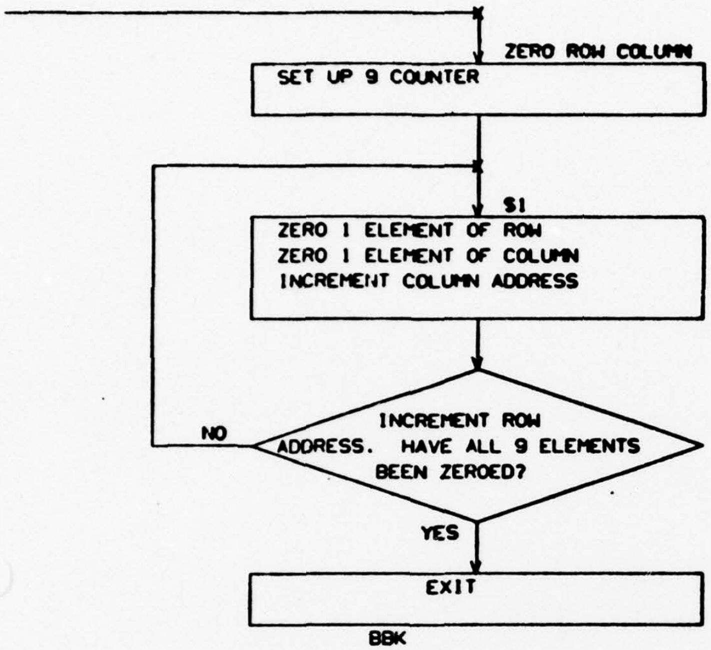
COMPUTE -(M)(X) ADD MEASUREMENT (Y) SAVE RESIDUE

BBK

* MEASUREMENT UPDATE P
*
* UPDATE THE COVARIANCE MATRIX IF NEW STATE VECTORS WERE GENERATED.
*



- ZERO ROW - COLUMN
-
- THIS ROUTINE WILL ZERO ANY ROW AND COLUMN OF A 9 X 9 MATRIX. THE
- ARGUMENTS CONSIST OF POINTERS TO THE ROW AND COLUMN.
-



```
*                              REGISTER SET UP
*
* THIS ROUTINE WILL CREATE 14 REGISTERS AND SET UP COMMON POINTERS
*
```

REG SETUP

CREATE REGISTERS
SET POINTER TO TEMP VECTOR
SET POINTER TO M MATRIX
SET POINTER TO P MATRIX
SET UP TWO 9 COUNTERS

BBK

3.3 COMPUTER SUBPROGRAM ENVIRONMENT

3.3.1 Kalman Filter Tables

a) Velocity Variance: This table is used to define the initial variance for the P matrix diagonal elements for velocity. There is an entry in the table for each velocity mode. It is described in detail in the listing. The official name of this table is SIGMA NRA.

b) Overflow Protection: This table is used to define the maximum value for the first three diagonal elements of the P matrix. The two entries for position are 80 nautical miles squared and the entry for T zero is half of 441 microseconds squared. The table is described in the listing. The official name of this table is DATA TABLE.

c) Tables Proportional to Frequency: There are four tables in KALMAN that have three entries each that differ only in frequency. The first entry is for the 10.2 frequency, the second is for 13.6 and the last is for 11.3. The official names of these tables are LAMBDA TABLE, V LAMBDA, M4 TABLE and TF LAMBDA CONSTANT TABLE. They are described in detail in the listing.

d) Phi Matrix Definition: This table identifies the elements of the Phi matrix that are not zero or, in the case of the diagonal elements, not unity. The first nine MSB's of each entry define one row of the Phi Matrix. The nine entries define the nine rows of Phi in order. A one in a bit position indicates that the appropriate term is a zero (one unity). The official name of this table is PHI CODE.

e) Station Locations: This table contains the location of all existing OMEGA transmitting stations. Each location is specified as a three element geocentric position A. The table is defined in detail in the listing. The official name of this table is STATION VECTOR TABLE.

3.3.2 Temporary Storage

Kalman requires 18 words of temporary storage called KAL TEMP in addition to words added to the R15 pushdown stack.

3.3.3 Input/Output Formats

Not applicable.

3.3.4 Required System Library Subroutines

Subroutine	Flow Diagram	Subprogram Design Document (by Volume Number)
ATAN	P17/4	XII
CROSS PRODUCT	P17/4	XII
DOT PRODUCT	P17/4	XII
D PHI KI	P20/4.7	XII
Matrix 30	P17/2	XII
RESOLVE	P6/2	XII
ROTATE Reg's	P5/4	XII
SIN	P17/5	XII
SQRT	P17/4	XII
THETA 1	P17/4	XII
THETA C	P20/4 P20/7	XII